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NORTHWEST AFRICA

A CLIMATOLOGICAL STUDY

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REVIEW AND APPROVAL STATEMENT

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13. Abstract: A climatological study of Northwest Africa, including Algeria, Tunisia, Morocco, Western Sahara, and the northern parts of Mauritania, Mali, and Niger. After describing the general geography of land areas in Northwest Africa, the major meteorological features of the entire study area are discussed. The geography and major climatic controls of each of the two "climatic commonality" regions that constitute Northwest Africa are outlined in separate chapters, with a detailed description of each "season," including typical weather, clouds, visibility, winds, precipitation, temperature, and additional hazards.

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INTRODUCTION

AREA OF INTEREST. This study describes the geography, climatology, and meteorology of Northwest Africa. This area, as shown in Figure 1-1, has been divided into two "zones of climatic commonality"; these zones will be described separately.

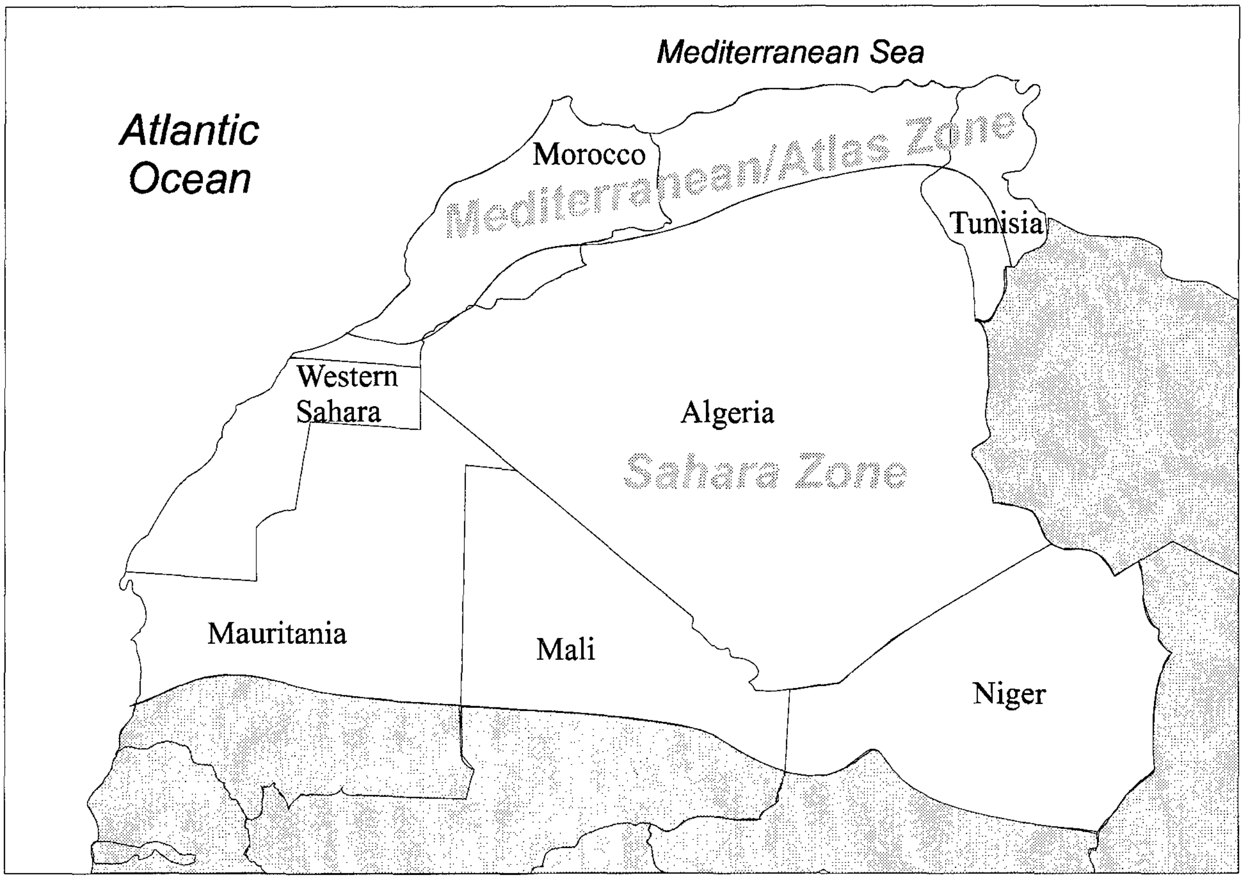


Figure 1-1. Northwest Africa. Figure shows Northwest Africa and its two climatic zones.

• ***The Mediterranean / Atlas Zone.*** This zone experiences a truly Mediterranean climate, with mild wet winters and warm, dry summers. The northern boundary is the Mediterranean Sea, and the southern boundary is the line where the mean annual precipitation falls below 100 mm, which approximately coincides with the southern extent of the Atlas mountains. In the west, the region's bordered by the Atlantic Ocean. The border between Tunisia and Libya marks the zone's eastern boundary. This zone includes most of Morocco, and the northern portions of Tunisia and Algeria. The region also includes the ranges of the Atlas mountains, which shield the area from the hot, dry Sahara.

• ***The Saharan Zone.*** This zone covers the majority of Northwest Africa, including all of Western Sahara, most of Algeria, and the northern portions of Mali, Mauritania, and Niger. Dominated by the vast Sahara, this region is bordered on the south by the line where mean annual rainfall exceeds 250 mm (the area south of this line is described in USAFETAC/TN—95/001, *Equatorial Africa*).

Study Content. Chapter 2 provides a general discussion of the major meteorological features that affect Northwest Africa. These features include semipermanent climatic controls, synoptic disturbances, and mesoscale and local features. The individual treatments of each region in subsequent chapters do not repeat descriptions of these phenomena; instead, they discuss specific effects of these features unique to that region. Therefore, meteorologists using this study should read and consider the general discussion in Chapter 2 before they try to understand or apply the individual climatic zone discussions in Chapters 3 and 4. This is particularly important because the study was designed with two purposes in mind: first, as a master reference for Northwest Africa; and second, as a modular reference to each individual region.

Chapters 3 and 4 amplify the general discussions in Chapter 2 by describing the geography, climate, and meteorology of the regions shown in Figure 1-1. These chapters provide detailed discussions of the regions that are known to feature reasonably homogeneous climatology and meteorology. **Note:** in mountainous areas, weather and climate are not necessarily internally homogeneous, but they are distinctly different from that of the areas immediately adjacent.

Each chapter first discusses geography (including topography, rivers and drainage systems, lakes and water bodies, and vegetation), major climatic controls, and, if appropriate, special climatic features. Weather for each season is then discussed, highlighting the following elements:

General Weather	***Precipitation***
Sky Cover	*Thunderstorms*
Visibility	*Temperature*
Winds	*Additional Hazards*

Conventions. The spellings of place names and geographical features are those used by the Defense Mapping Agency's Aerospace Center (DMAAC). Distances and elevations are in meters below 10 kilometers and in kilometers (km) above. Cloud and ceiling heights are in feet. When the term "ceiling" is used it means greater than 4/8 cloud coverage *at any level* unless specified otherwise. Temperatures are in degrees Celsius (° C) unless specified otherwise. Wind speeds are in knots. Precipitation amounts are in millimeters (mm). Most synoptic charts are given in Universal Coordinated Time (UTC). When synoptic charts are not provided, only local time (L) is used.

While the meteorological community has gone to the term "hectopascals" as the pressure unit, Air Force weather usage remains "millibars." Therefore, we have elected to remain with "millibars" (mb) for audience convenience.

Unless otherwise stated, cloud bases are reported in feet above ground level (AGL); tops are above mean sea level (MSL). Since cloud bases are generalized over large areas, readers must consider terrain in discussions of cloud bases in and around mountains.

Mean monthly rain, snow, and thunderstorm days are derived from World Meteorological Organization present weather codes. "Rain days" include those on which WMO present weather codes 21, 23-26, 50 through 69, 80 through 84, 91, 92, 94-97, or 99 are reported. "Snow days" include days on which present weather codes 22, 23, 70-75, 77, or 85-88 are reported. "Thunderstorm days" are those on which codes 17 or 91-99 are reported. A "fog day" is one on which code 40-49 is reported.

Data Sources. Most of the information used in preparing this study came from two sources within AFCCC. Studies, books, atlases, and so on were supplied by the Air Weather Service Technical Library (AFCCC/DOL). Climatological data came directly from the Air Weather Service Climatic Data Base, through OL-A, AFCCC—the division of AFCCC responsible for maintaining and managing this database.

Related References. This study, while more than ordinarily comprehensive, is certainly not the only source of climatological information for the military meteorologist concerned with Northwest Africa. USAFETAC/DS—87/034, *Station Climatic Summaries-Africa*, provides summarized meteorological observational data for several major airports in the study area. Staff weather officers and forecasters are urged to contact the AWS Technical Library for more data on the study area.

Chapter 2

MAJOR METEOROLOGICAL FEATURES OF NORTHWEST AFRICA

Sea-Surface Conditions. Ocean currents play an important role in determining the climate of the region. Warm waters destabilize the boundary layer, producing cumuliform clouds, while cold waters stabilize the boundary layer, leading to the development of stratiform clouds. Figure 2-1 shows the prevailing directions of the ocean currents near the study area.

The currents in the Mediterranean Sea are relatively weak. The Mediterranean loses nearly three times as much water to evaporation as it receives through rainfall and runoff. This imbalance is compensated by a constant flow of water from the Atlantic through the Strait of Gibraltar. This incoming water forms a surface current flowing eastward along the coast of North Africa. This is the only well-defined current in the Mediterranean.

The cold Canary Current, flowing north-south, has a profound effect on the weather along the Atlantic coast of Northwest Africa. Upwelling along the coast brings cold water to the surface, cooling the lowest layers of the atmosphere, bringing dense fog and stratus ceilings to the coast of Morocco and Western Sahara. These conditions normally occur

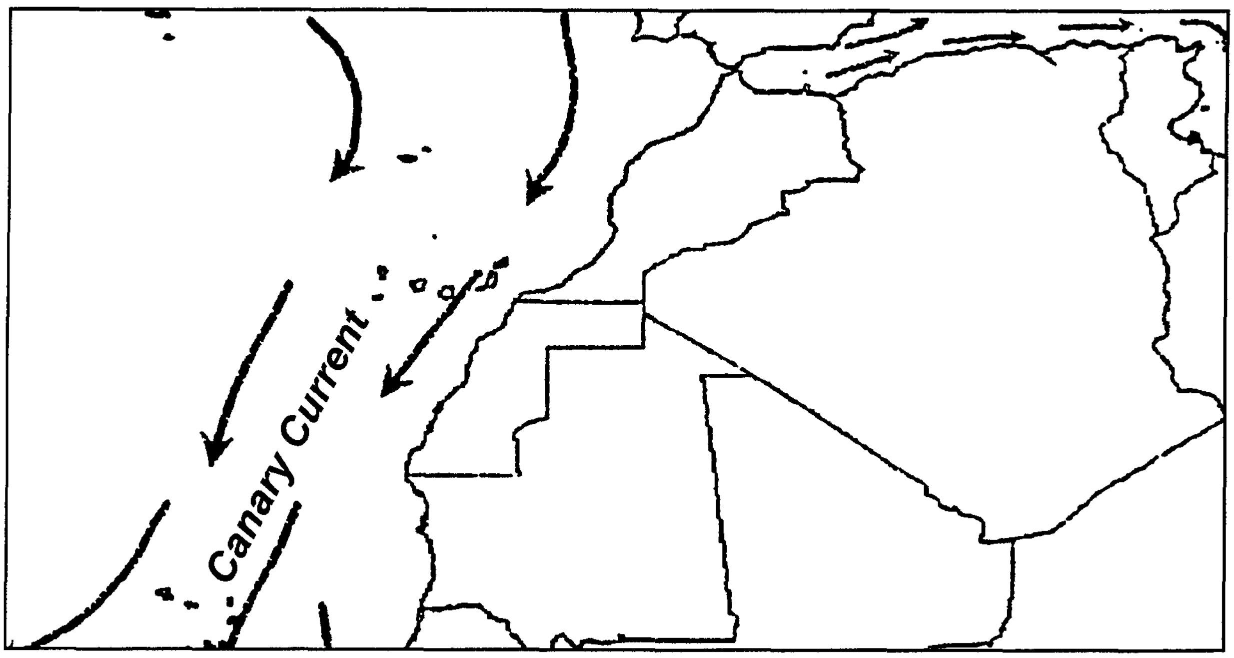


Figure 2-1. Prevailing Direction of Ocean Currents in the Vicinity of Northwest Africa. The bold arrows show the cold Canary Current flowing from the north; the light arrows show the weak Mediterranean.

during the morning within 30 km of the coast. Coastal fog and stratus are most prevalent during the summer, when the temperature difference between land and sea is greatest. The cold waters of the Canary Current are apparent in Figure 2-2. July sea-surface temperatures along the Northwest African coast average 20-21° C, while farther south, water temperatures rise dramatically as the influence of the Canary Current weakens.

The relatively warm waters of the Mediterranean enhance precipitation in the region during winter. January sea temperatures over the central Mediterranean average about 2° C higher than the air temperature. As cold air moves over this warm water, convective instability results, leading to deep cumulus development and the formation of Mediterranean depressions (see the discussion of Genoa Lows later in this chapter).

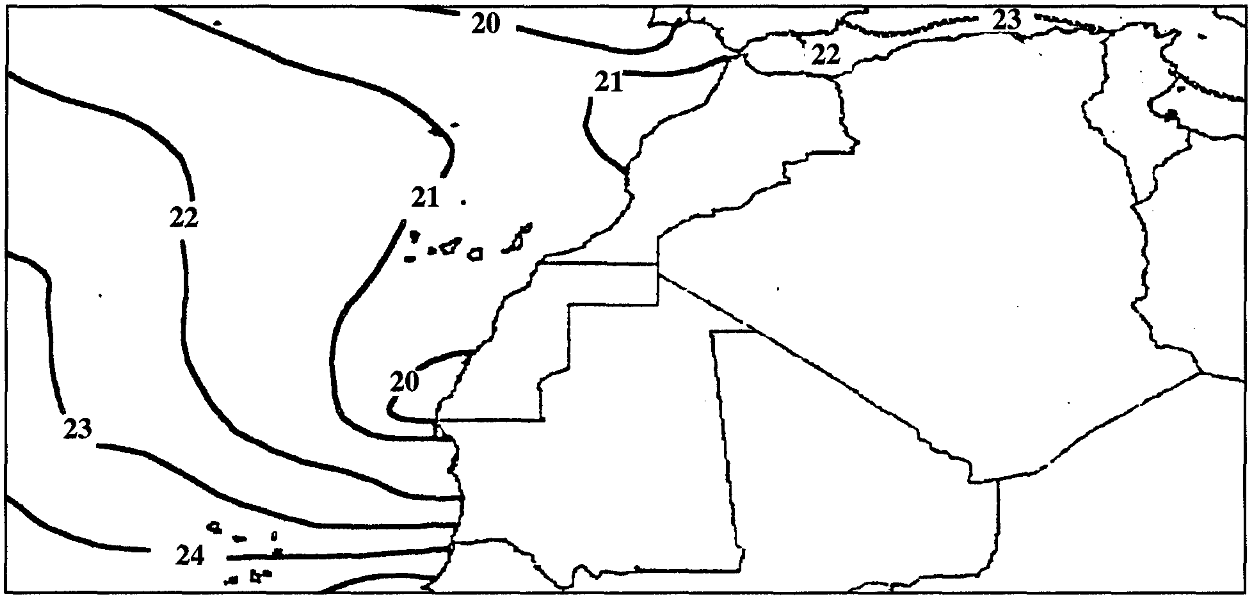


Figure 2-2a. Mean July Sea-Surface Temperatures (° C). The isopleth lines show the difference in Sea-surface temperatures that impact weather conditions along coastal Northwest Africa.

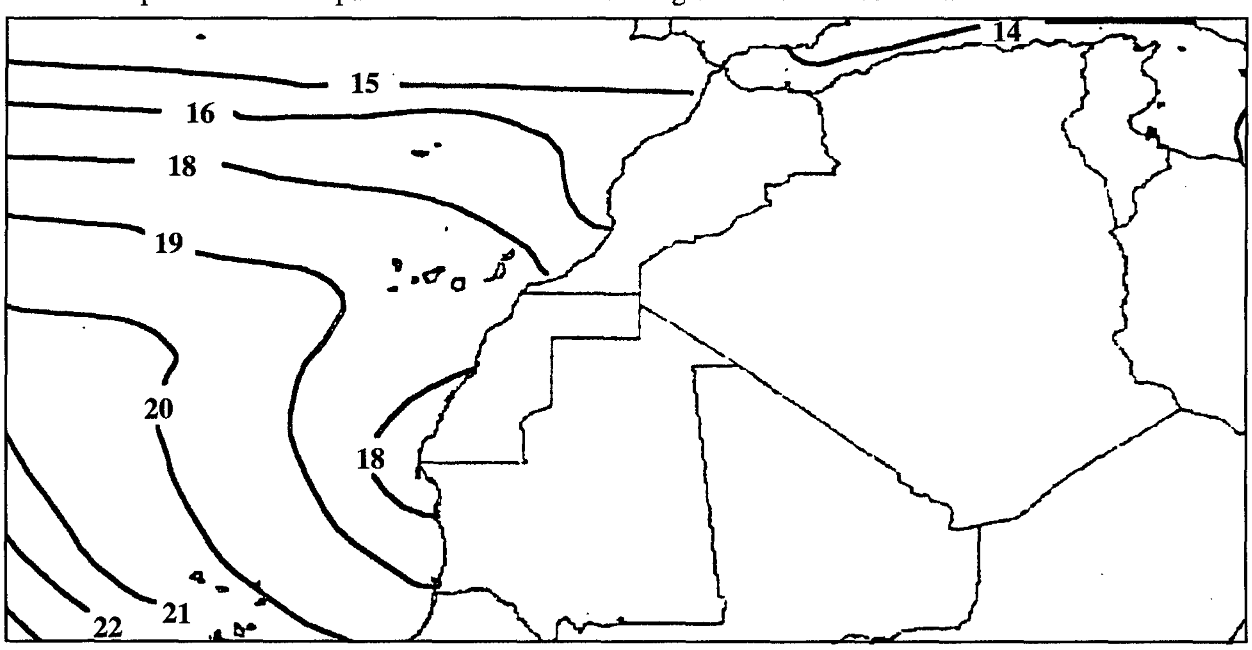


Figure 2-2b. Mean January Sea-Surface Temperatures (° C). The isopleth lines show the difference in Sea-surface temperatures that impact weather conditions along coastal Northwest Africa.

Maritime Atmospheric Pressure Features. The primary maritime pressure features affecting the climate of Northwest Africa are the Azores High and the South Atlantic High.

Azores High. This semipermanent high-pressure cell is a very important part of the atmospheric circulation pattern over Northwest Africa. The high strengthens and moves northward in the summer, preventing frontal systems that traverse Europe from reaching Africa's Mediterranean coast. Thus, the hot, dry conditions that typify Mediterranean summers prevail. In late October, the high weakens and moves south, allowing fronts to invade Africa's Mediterranean coast (though the Atlas Mountains prevent the vast majority of these systems from reaching the Sahara). Flow from the Azores High is modified as it crosses the desert, becoming very hot, dry, and dust-laden. Figures 2-3a and 2-3b show the Azores High's mean position and sea-level pressure for January, April, July, and October.

South Atlantic (St. Helena) High. Figures 2-3a and 2-3b show this high's mean position and sea-level pressure during January, April, July, and October. Mean pressure reaches 1,025 mb in September. The cell migrates northwestward from 32° S, 8° W in January to 26° S, 12° W in July. Surface wind speeds average 13 knots to its north and 25 knots to its south along the mid-latitude storm track. The high slopes equatorward with height.

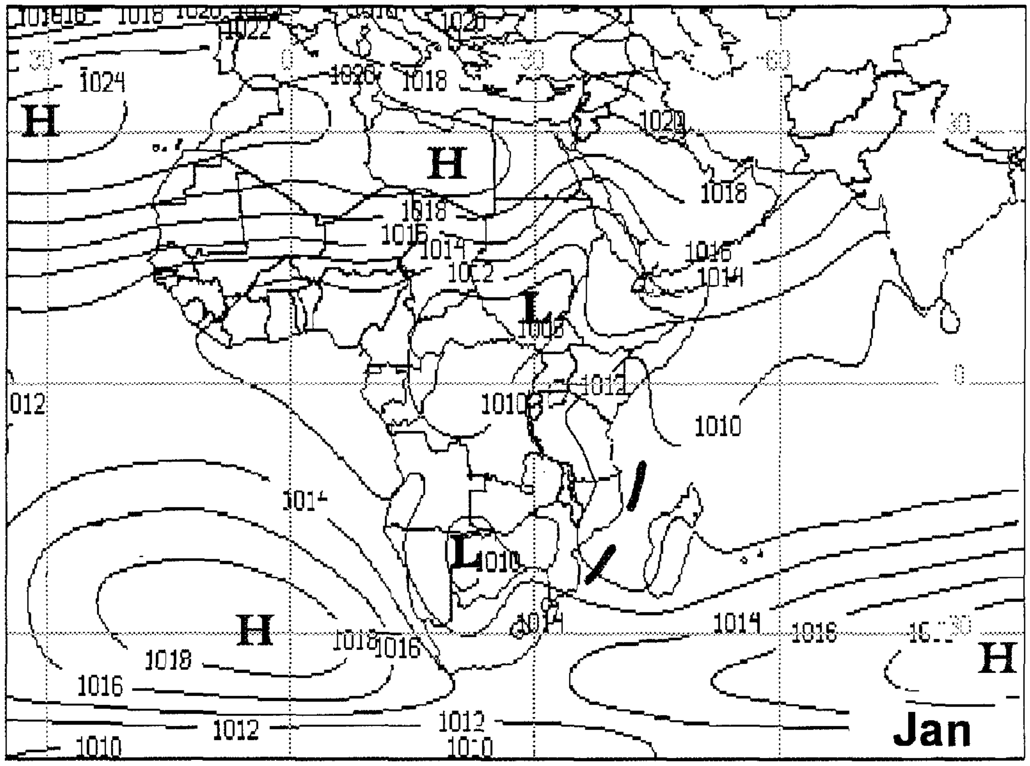


Figure 2-3a. Mean January Surface Pressure Fields (mb). The isobar analysis show the relative strength of the semipermanent high pressure systems that impact Northwest Africa.

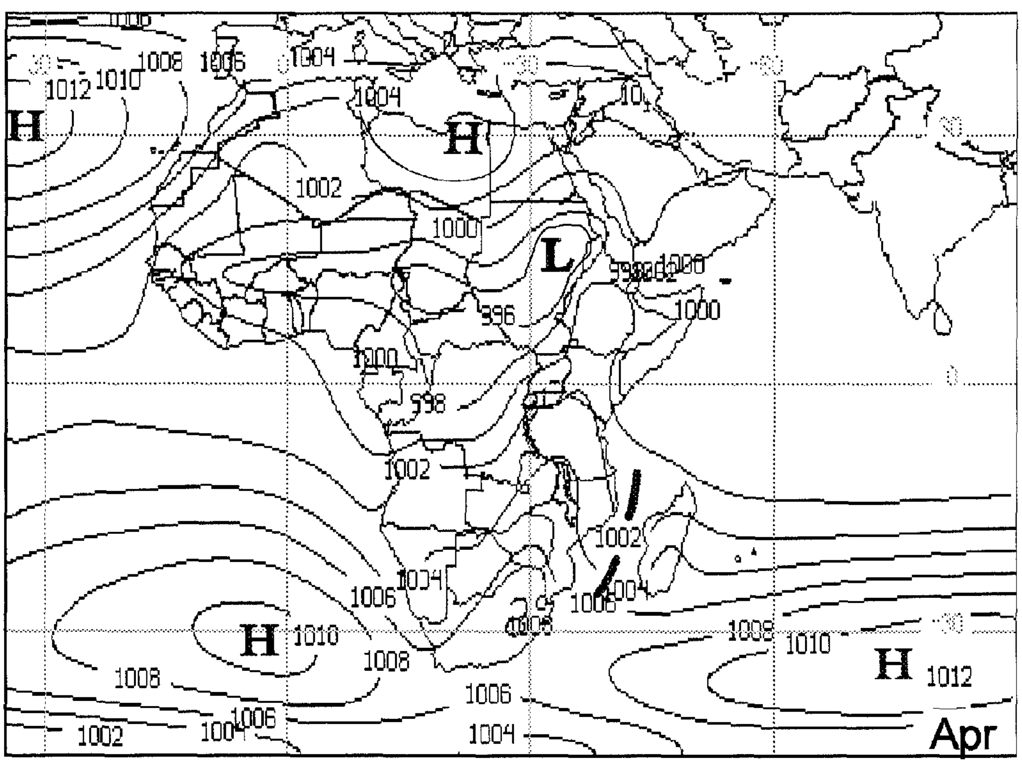


Figure 2-3b. Mean April Surface Pressure Fields (mb). The isobar analysis show the relative strength of the semipermanent high pressure systems that impact Northwest Africa.

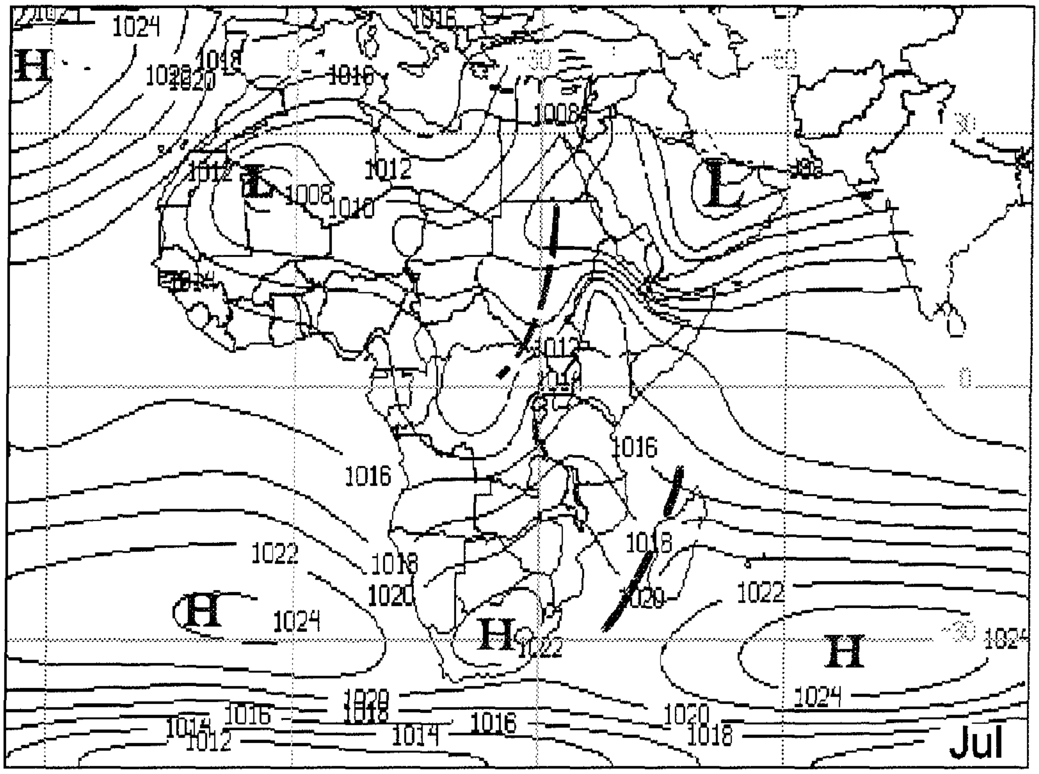


Figure 2-3c. Mean July Surface Pressure Fields (mb). The isobar analysis show the development of the Saharan Heat Low.

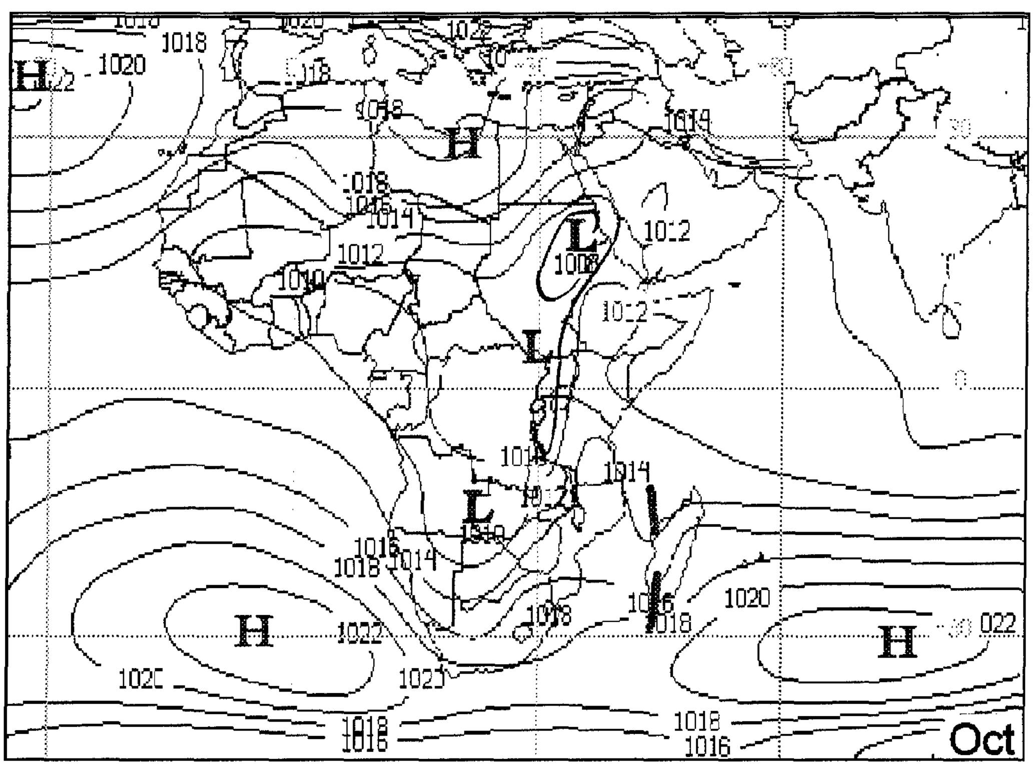


Figure 2-3d. Mean October Surface Pressure Fields (mb). The isobar analysis show the filling of the low as autumn begins.

Continental Atmospheric Pressure Features. The continental atmospheric pressure features affecting the climate of Northwest Africa are the Saharan High, the Saharan Heat Low, and the Sudanese Heat Low.

The Saharan High. This high pressure feature, part of the subtropical belt of high pressure, is normally centered in the eastern Sahara. It develops in October or November and persists through the winter. The Azores and Saharan Highs often combine to produce an extensive high-pressure ridge over northern Africa. The dynamic origins of this high help to explain the Sahara's arid conditions. Air near the equator is heated by the intense insolation resulting from the high angle of the sun, and through latent heat of condensation released by the great mass of clouds forming in the Near Equatorial Tradewind Convergence (NETWC) zone (see discussion of the NETWC later in this chapter). The heated air rises, moves poleward at high levels, and assumes a westerly component due to the earth's rotation. At about 30° N, these winds converge into a band of strong westerlies (the subtropical jet). This convergence aloft leads to subsidence below and produces the belt of high pressure at the surface that includes the Saharan High. This subsiding air and the Sahara's lack of oceanic influences produce atmospheric conditions extremely unfavorable for the formation of clouds and rain.

The Saharan High's day-to-day position and strength vary as troughs enter northern Africa, particularly between January and early April. During winter, strong nighttime radiative cooling enhances the surface strength of the Saharan High. The high generally moves eastward ahead of disturbances or disappears entirely off the synoptic chart; it usually reforms at the surface 12-24 hours after a frontal passage. Figures 2-3a, 2-3b and 2-3d show the January, April, and October positions and mean sea-level pressures of the Saharan High. In April, the Saharan High's mean position shifts slightly eastward to 22° E due to increased daytime heating and an increase in Atlas Low activity. By the time the Saharan High outflow crosses the desert, the air is hot, dry, and dust-laden. The northeasterly winds produced by this high are called the *Harmattan*; the dust-laden air is known as *Harmattan Haze* (see the Mesoscale and Local Effects section).

Saharan Heat Low. This low develops over the Sahara near 25° N, 3° E in late March or early April and lasts until mid-October. By July, the mean surface pressure is 1008 mb (Figure 2-3c). The Saharan Heat Low is sustained through summer by intense surface heating and can extend to 750 mb. This low anchors the western end of the large-scale low-pressure trough extending from Pakistan westward to the Sahara. This persistent circulation introduces large amounts of dust into the atmosphere and assists in Atlas Low development.

Sudanese Heat Low. Varying from 1,004 to 1,012 mb, this low often marks the eastern edge of large-scale equatorial African low pressure in the Northern Hemisphere. The Sudanese Low lies over the elevated plateaus of southeastern Sudan and southwestern Ethiopia between December and March (Figure 2-3a). It migrates northward to 15-20° N in April and May. Between June and September, it degenerates into the broad, poorly defined low-pressure area shown in Figure 2-3c; it reappears as a closed low in October.

Monsoon Climate. The term "monsoon" (from the Arabic *mausim*, or "season") is commonly applied to those areas of the world where there is a seasonal reversal of prevailing winds, but the generally accepted definition of a monsoon climate includes satisfaction of the following four criteria (after Ramage, 1971):

• The prevailing seasonal wind direction changes by at least 120 degrees between summer and winter,

• Summer and winter mean wind speeds both equal or exceed 10 knots (5 m/s),

• Wind directions and speeds remain steady, and

• No more than one system consisting of a low and a high may occur during January or July in any 2-year period within a 5-degree square surrounding the area.

Figure 2-4 shows the extent of the monsoon climate across Africa. Only the extreme southeastern portion of Northwest Africa is affected by the monsoon circulation.

Near Equatorial Tradewind Convergence (NETWC). Also called the Intertropical Convergence Zone (ITCZ) and the Meteorological Equator, the NETWC marks the boundary between the two monsoon wind regimes. Southeasterly flow occurs south of the NETWC, northeasterly flow to its north. The NETWC affects only the extreme southern portion of Northwest Africa and only during the summer, when the NETWC reaches its northernmost position (normally near 20° N).

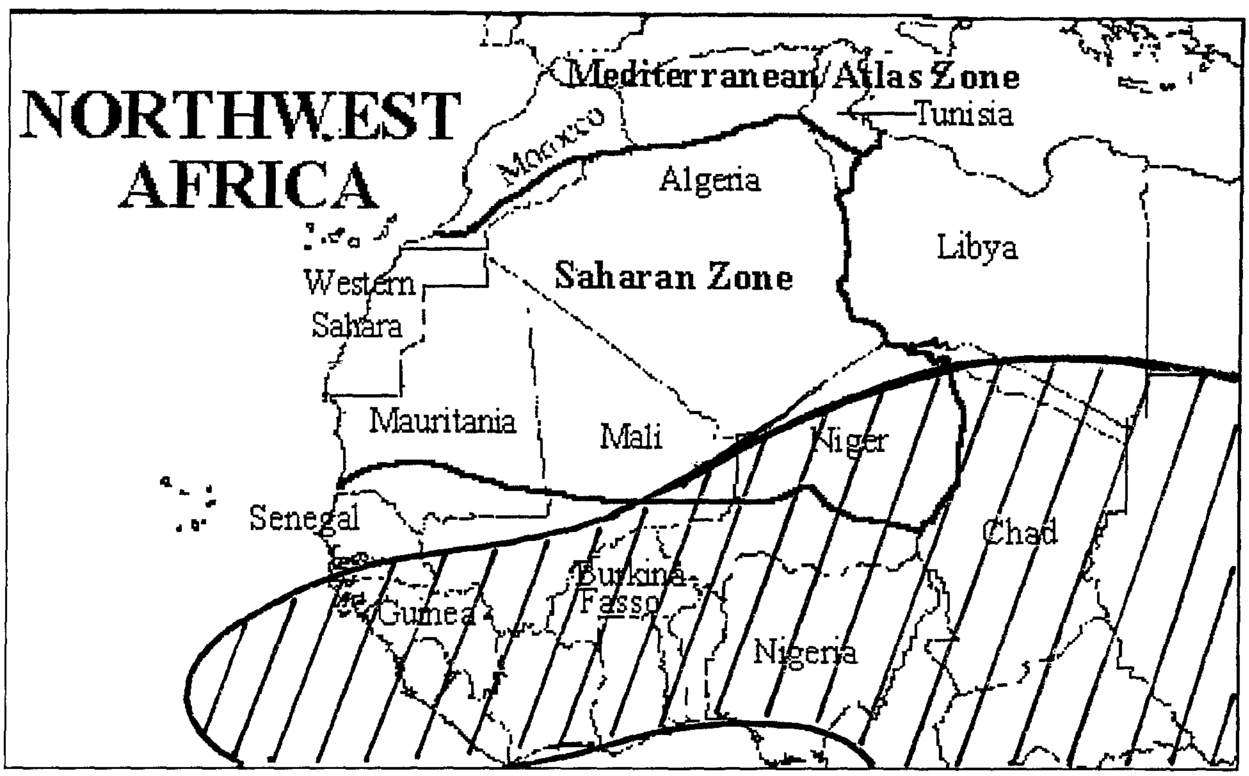


Figure 2-4. **Monsoon Climate (hatched area) Across Africa (Ramage, 1971).** Figure shows the portion of Northwest Africa affected by the monsoon climate.

The NETWC forms when the outflows from the Northern and Southern Hemispheres' subtropical highs converge. Although convection frequently occurs, there is rarely a continuous line of convection along the NETWC axis. "Trade wind troughs" (or trade wind convergence zones) and "monsoon troughs" are common terms referring to specific forms of the NETWC. Trade wind troughs coincide with confluence between northeasterly and southeasterly trade wind flow, and most associated cloudiness occurs along the axis of confluence. Monsoon troughs are characterized by a directional shear zone, with westerlies on the equatorward side and easterlies on the poleward side. Most associated cloudiness occurs equatorward of the trough.

A trade wind trough sometimes forms over the Atlantic, with convection occurring near the trough axis. The Atlantic's moderating influence keeps the trough in a fairly narrow latitude band. In spring, North Atlantic coastal waters are cooler than the Sahara, so the trough's northward movement near the west coast is delayed, and the wet season is shortened in and around Senegal. South Atlantic coastal waters are cool year-round, so the trough does not move into the Southern Hemisphere unless an El Niño-like event occurs.

Figure 2-5a (next page) shows the mean position of the NETWC during July and August, when it's at its northernmost point. The satellite image in Figure 2-5b shows typical convection associated with the NETWC. Note that although the NETWC is over the southern Sahara, most of the convection remains south of the Sahara. There is some isolated convection, however, over high terrain in northern Mali and Niger.

Intertropical Discontinuity (ITD). The ITD is a local name for the NETWC. It's a monsoon trough over western Africa produced by the convergence of outflows from the Azores and South Atlantic Highs. Dry, subtropical Saharan air lies north of the ITD, while moist, equatorial Atlantic air lies to the south. The ITD slopes to the south with height, and convection develops well south of the surface trough. This monsoon trough follows the sun's annual movement, trailing it by about 6 weeks. However, the trough's northward movement is more gradual than its southward movement. In March, the Azores and Saharan Highs are still strong, but they weaken significantly in April and May, allowing the surface monsoon trough to gradually move northward. Between December and July, the South Atlantic High strengthens and moves from 32 to 26° S, helping to drive the trough northward. The ITD is farthest north in July and August. Brief 1-3 day northward surges occur from March to May, when deep Atlas Lows temporarily weaken or replace the Azores-Saharan High-pressure ridge over the Sahara. Northward shifts usually span about 90 km, but the ITD has moved 12 degrees of latitude in 24 hours. The return southward is generally faster, as the Saharan High becomes reestablished and the South Atlantic High weakens and moves south.

The ITD extends to about 600 mb. Its mean July position is 15° N at 850 mb and 9° N at 700 mb. Its mean January position is 3° N at 850 mb and 7° S at 700 mb. The surface position of the ITD is marked by wind shifts and humidity contrasts. On the north side of the ITD, winds are generally northerly to easterly at low- and mid-levels, while winds to the south are southerly to westerly. The two contrasting air masses also produce the thermally-driven North African Mid-tropospheric Easterly Jet (MTEJ), which produces small areas of upper-level divergence. This increases low-level convergence, which enhances cloud cover and rainfall (See the discussion of the MTEJ under Jet Streams later in this section).

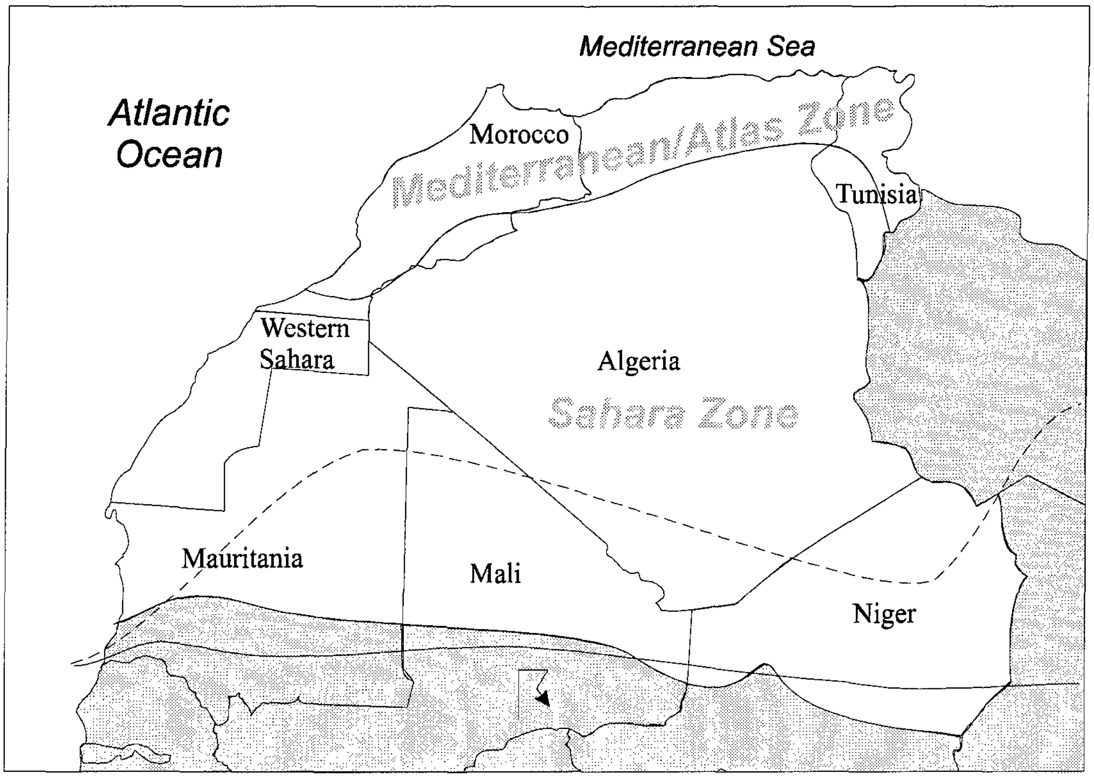


Figure 2-5a. Mean July/August position of NETWC. The dashed line shows the position of the NETWC ; the solid line shows location of associated convection.

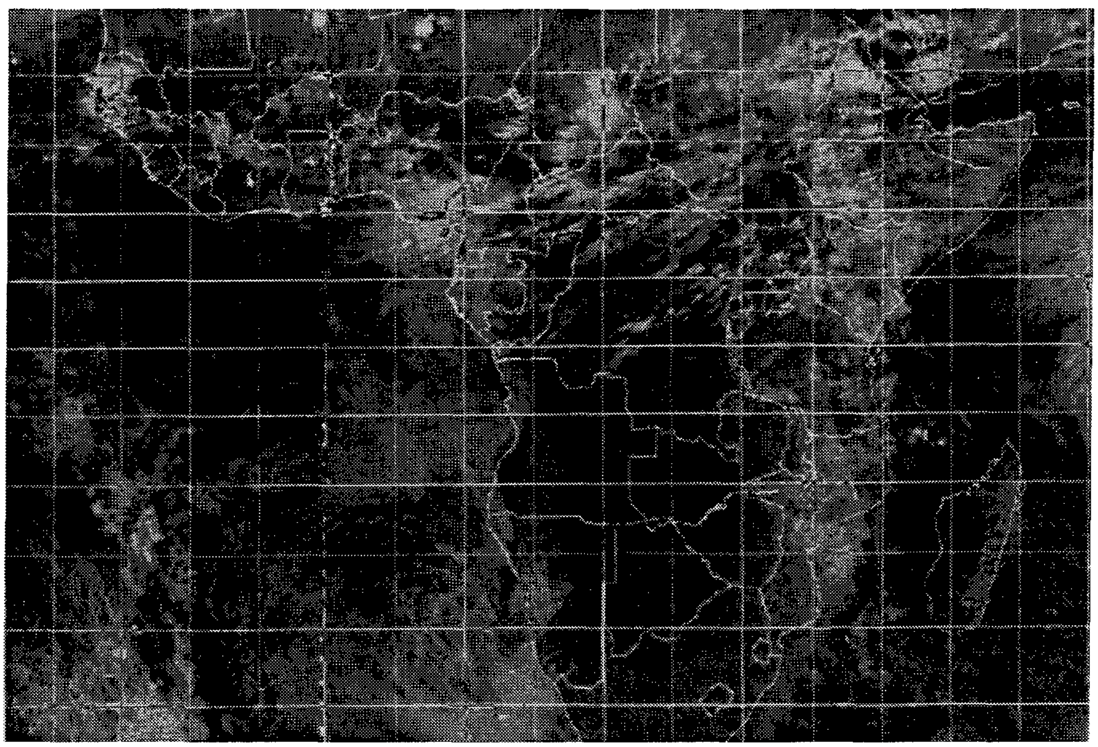


Figure 2-5b. NOAA visual image July, 28, 1988. Isolated convection appears over high terrain in central Mali and Niger.

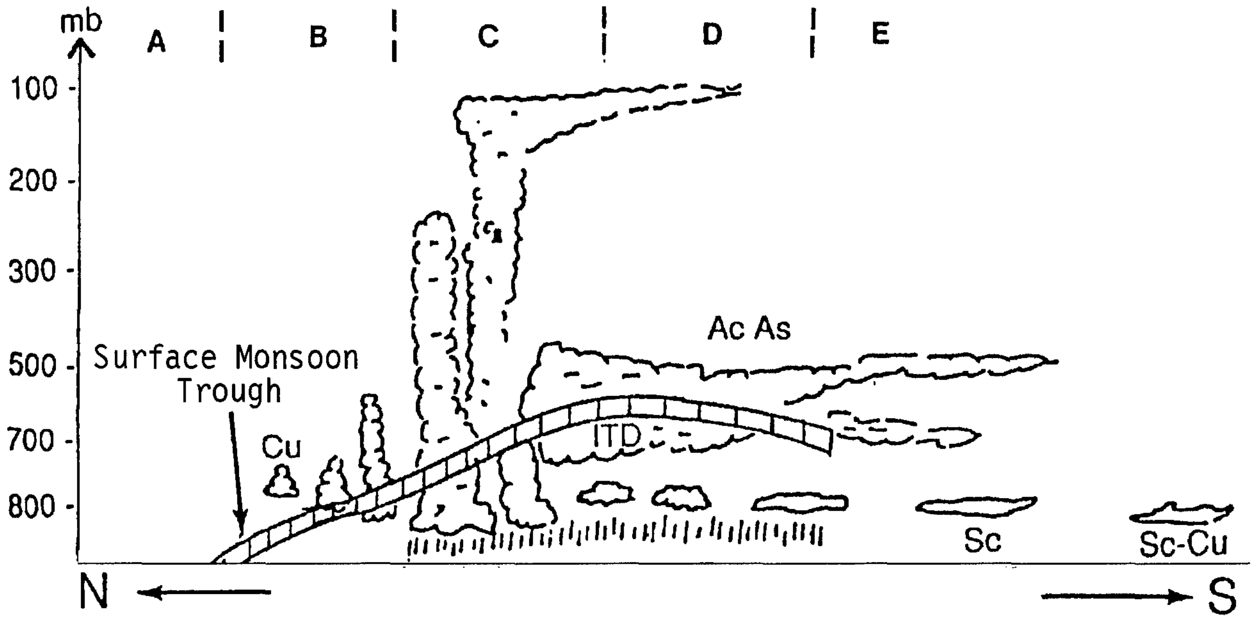


Figure 2-6. Vertical Cross Section of the "African Interior" Monsoon Trough and the Intertropical Discontinuity (ITD) (Omotosho, 1984). Figure shows the types of weather that occur in various zones of instability along the ITD.

Figure 2-6, a vertical cross section through the ITD, shows that precipitation associated with the ITD occurs well south of the monsoon trough's surface position. The weather associated with the labeled zones (A, B, C, D, and E) is discussed below.

Weather along the ITD is often broken into zones determined by the depth and instability of the South Atlantic air mass and the amount of moisture available. The warm, dry air aloft caps the convection, which develops only if the moist layer is deep enough. Northwest Africa south of the Atlas Mountains is entirely within Zone A throughout winter; during summer, portions of the extreme southern Sahara occasionally exhibit weather associated with Zone B, and on very rare occasions, Zone C. The zones move northward in spring at about 180 km a month and retreat southward in the fall at about 370 km a month.

• *Zone A* is north of the surface monsoon trough. This area experiences clear skies with hot, dusty daytime conditions and significant nighttime cooling. Winds are generally northeasterly across the Sahara. Harmattans and Harmattan Haze occur here.

• *Zone B* extends from the surface Monsoon Trough southward 250 to 450 km. Fair weather cumulus dominates in the afternoon. Isolated showers and some thunderstorms (fewer than five a month) develop, but the limited moisture within the shallow South Atlantic air mass usually keeps monthly rainfall under 75 mm.

• *Zone C* is 550 to 750 km wide, but its boundaries are poorly defined, particularly between it and Zone D. The ITD is higher here and provides more moisture, but rainfall amounts vary considerably by season and location. Precipitation is normally in the form of showers and thunderstorms associated with African waves and squall lines (see Synoptic Disturbances).

Weather associated with Zones D and E does not occur in Northwest Africa.

Trade-Wind Inversions. The South Atlantic and Indian Ocean Highs slope toward the equator with height, producing subsidence inversions over the trade winds. Strongest over the northwest and southwest coasts of Africa, trade wind inversions produce primarily stable conditions, preventing precipitation and trapping moisture in the lower layer. Relative humidity is greater than 70 percent below the inversion but less than 50 percent above.

Mean inversion height along Mauritania's coast is 500 m, but heights gradually rise toward the tropics. Areas with strong instability force the inversion higher; thus, inversion tops are usually higher in summer than in winter and higher over land than water.

Jet Streams. The following jet streams affect Northwest Africa: the polar jet (PJ), the subtropical jet (STJ), the tropical easterly jet (TEJ), and the mid-tropospheric easterly jet (MTEJ).

Polar and Subtropical Jets. The positions and movements of these air streams control cold air advection, steering, shear, and upper-level outflow for developing cyclones. Figure 2-7 shows the mean STJ positions for January and July.

Mean PJ positions vary north to south over Europe from 55 to 65° N. Maximum winds from December to March vary from 60 to 160 knots, becoming slower in summer. The PJ is usually found near 300 mb (30,000 feet or 9 km) MSL—slightly higher in summer. Southward deviations to 30° N are most frequent between December and March, but they can occur as late as June.

Initially, surface low-pressure cells develop when a strong PJ digs south of 30° N and forms a deep upper-level trough. The PJ and this trough may also intensify surface lows over the Mediterranean and in the lee of the Atlas Mountains. Northerly flow, which often develops on the east side of a blocking high-pressure ridge over the eastern Atlantic, can move the low eastward. The cold front/shear line may reach as far south as 10° N over central Africa.

Although the STJ shows less variability than the PJ in its daily position, its seasonal variability is greater. Mean STJ positions over the subtropics range from 22 to 45° N, but the STJ can reach 15° N during the winter. The southernmost position over West Africa occurs in February. Maximum wind speeds from December to April are between 80 and 180 knots at a mean height of 200 mb (39,000 feet or 12 km) MSL. Speeds between May and November are 30-60 knots at 39,000 to 42,000 feet or 12-13 km MSL. Winds are normally west-southwesterly. The STJ is weakest in July and August, seldom extending south of 35° N.

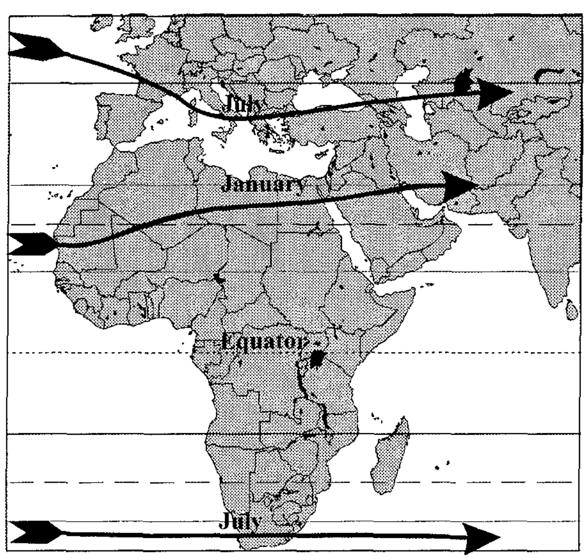


Figure 2-7. Mean January and July Position of the Polar Jet (PJ) and Subtropical Jet (STJ). There is no mean STJ in the Southern Hemisphere in January.

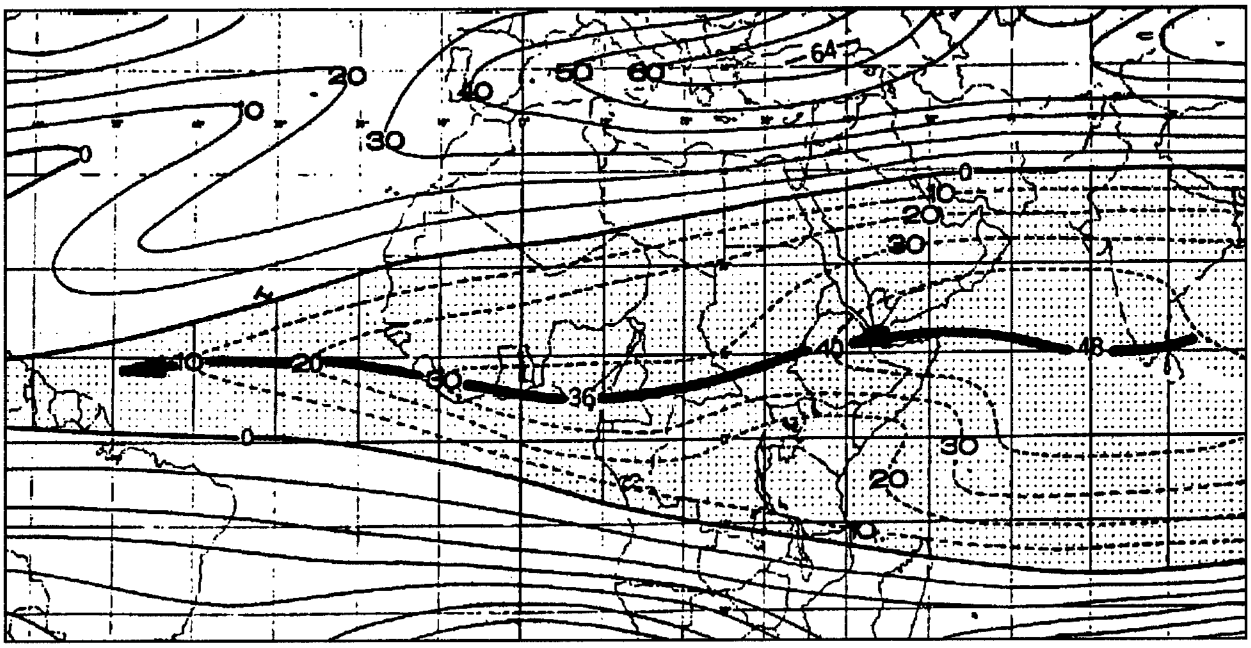


Figure 2-8. Mean July 200-mb Zonal Flow Showing the Tropical Easterly Jet (Arrow). The stippled area represents easterly flow; wind speeds are in knots.

Tropical Easterly Jet (TEJ). This Northern Hemisphere summer jet in the upper-level easterlies develops as outflow from the southern edges of the Tibetan Anticyclone. The TEJ provides an outflow mechanism for convection over sub-Saharan Africa, and changes in the TEJ can cause surges in convection. Its mean position is at about 10° N (4-5 degrees south of the ITD's surface position), but it oscillates between 5° and 20° N (see Figure 2-8). Maximum wind speeds exceed 100 knots between 100 mb (54,000 feet) and 200 mb (39,000 feet).

Another band of upper-level easterlies exists year-round over Africa, but its winds are weak, and without the Tibetan Anticyclone outflow, they do not truly constitute a jet. In February, the center reaches 10° S, with speeds averaging 35 knots. During the transition seasons, the center is near the equator, and speeds average 10-20 knots.

North African Mid-Tropospheric Easterly Jet (MTEJ). This mid-level jet occurs between May and October over subtropical Africa, developing along the foothills of the Ethiopian Highlands and extending westward to the Atlantic Ocean. It develops from the thermal contrast along the NETWC, where hot, dry Saharan air lies over cooler, moister equatorial air. The gradient is strongest during summer, when surface temperatures reach their maximum over the Sahara. The MTEJ steers African waves and squall lines westward. It aids development of African squall lines as it produces localized divergence aloft, enhancing cloud cover and rainfall. Mean jet core winds average 25 knots; maximum speeds reach 50 knots. Figures 2-9 and 2-10 show cross sections through the MTEJ. The easterly wind maximum correlates well with the mean height of the NETWC at 13° N during August.

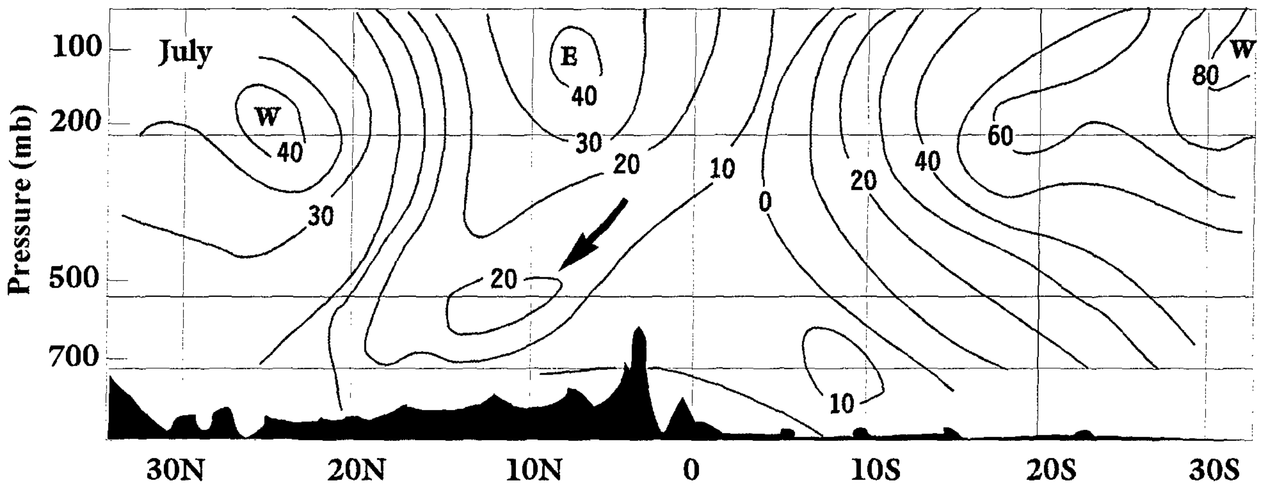


Figure 2-9. North-South Cross Section of Zonal Winds near 10° E for July. Solid lines are isotachs in knots; the arrow shows the location of the MTEJ. Terrain features are shown at bottom of figure.

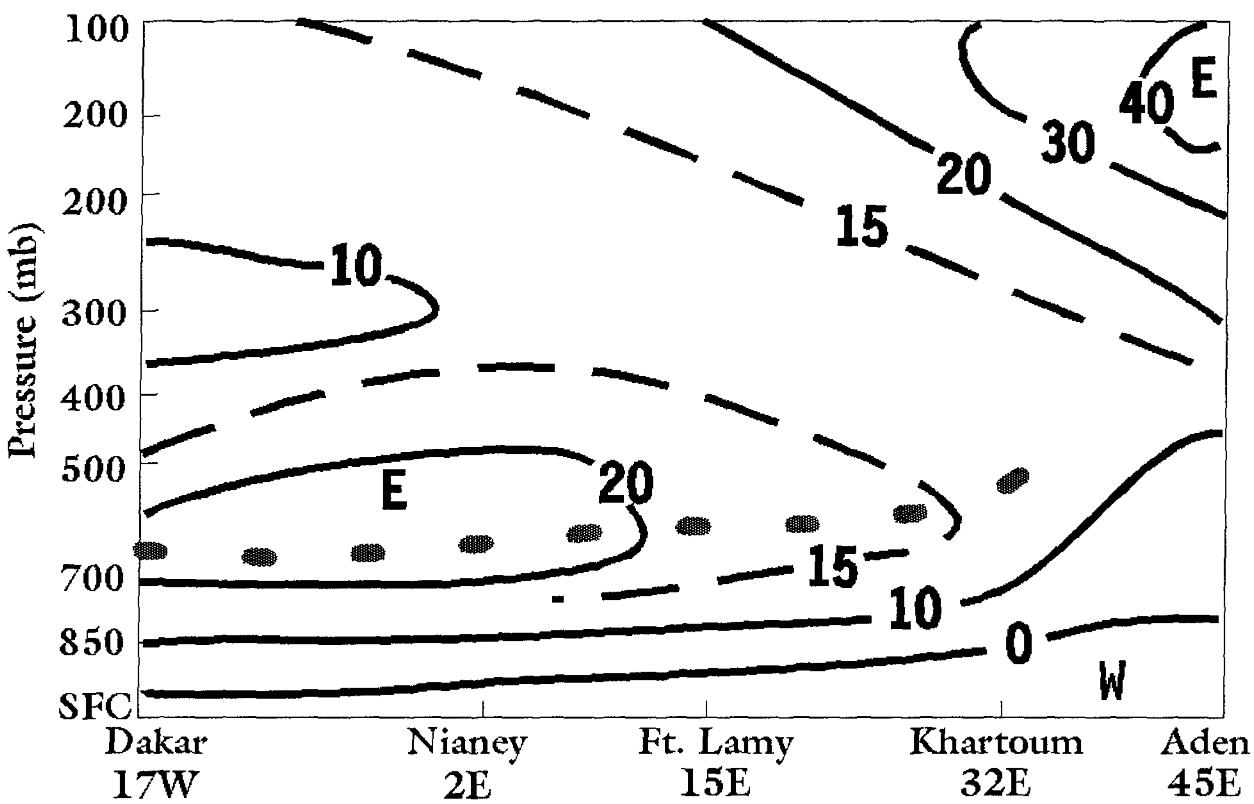


Figure 2-10. West-East Cross Section Showing the MTEJ at 13° N in August (Burpee, 1972). Solid lines are isotachs in 10 knot increments; dashed lines are isotachs in 5 knot increments. The dotted line shows the jet axis.

Mid- and Upper-Level Flow Patterns. Figures 2-11 through 2-14 show mean winds (knots) and heights (meters) during January and July at 850, 700, 500, and 200 mb over the study area.

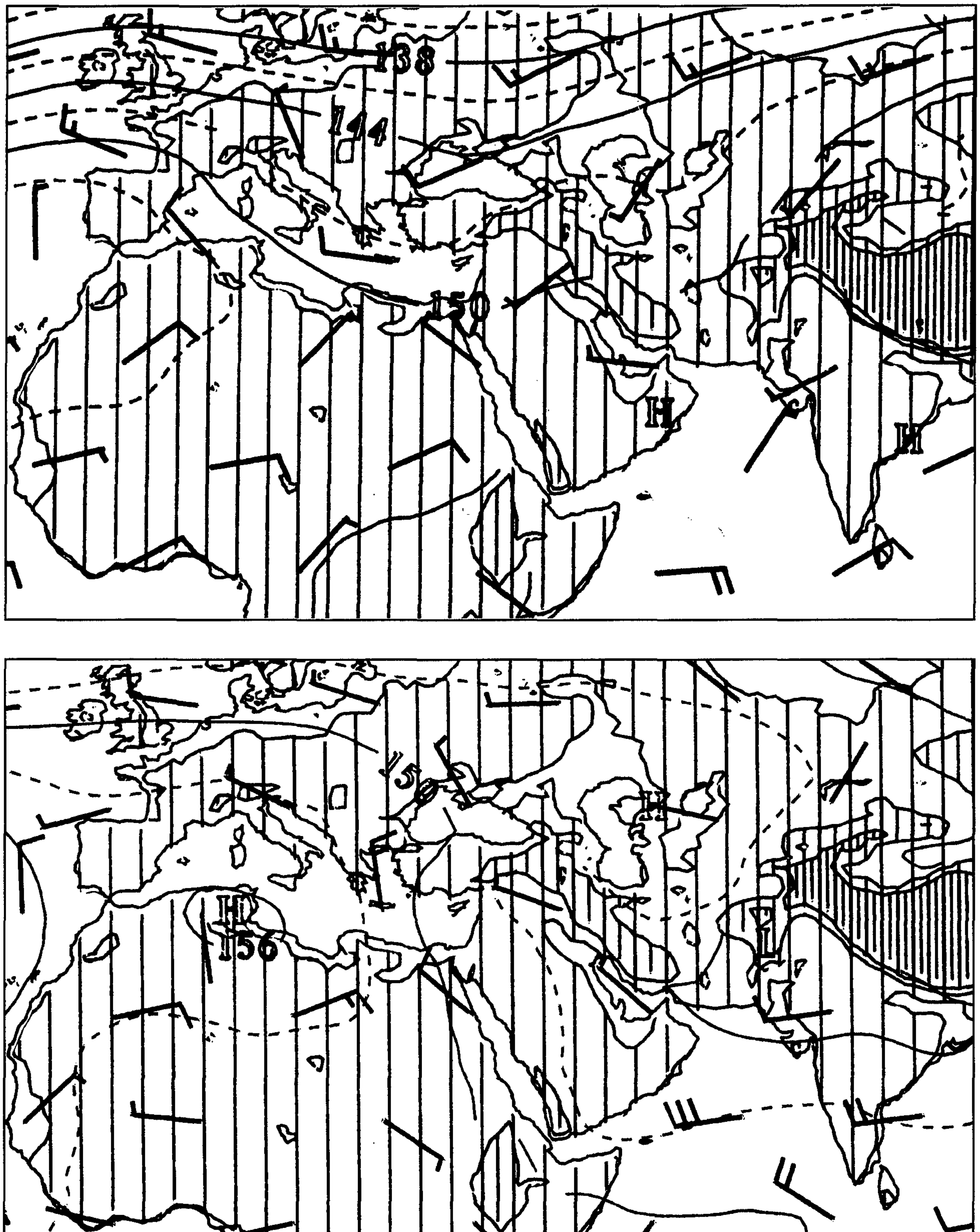


Figure 2-11. Mean January (top) and July (bottom) 850-mb Winds (knots) and Heights (meters). Local points of highest and lowest pressure are designated with H's and L's. Vector mean wind in 5-knot increments are shown. Winds less than 2.5 knots are depicted as a shaft with barbs. Contours of mean geopotential height (solid and dashed lines) in dekameters. Solid lines are labeled, dashed intermediate lines are unlabeled. Solid vertical lines indicate terrain elevations (tighter line spacing denotes higher elevation).

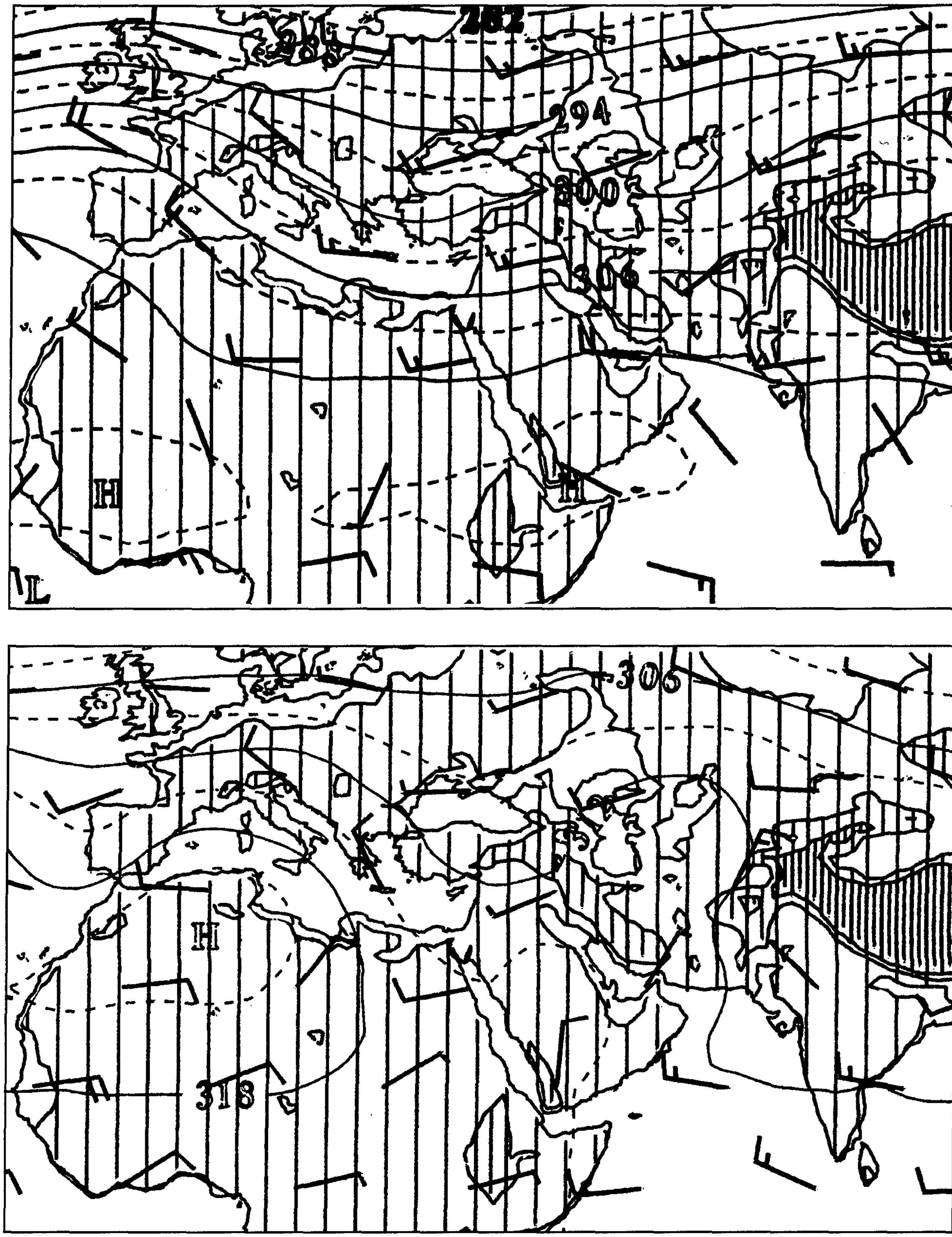


Figure 2-12. Mean January (top) and July (bottom) 700-mb Winds (knots) and Heights (meters). Local points of highest and lowest pressure are designated with "H"s and "L"s. Vector mean wind in 5-knot increments are shown. Winds less than 2.5 knots are depicted as a shaft with barbs. Contours of mean geopotential height (solid and dashed lines) in dekameters. Solid lines are labeled, dashed intermediate lines are unlabeled. Solid vertical lines indicate terrain elevations (tighter line spacing denotes higher elevation).

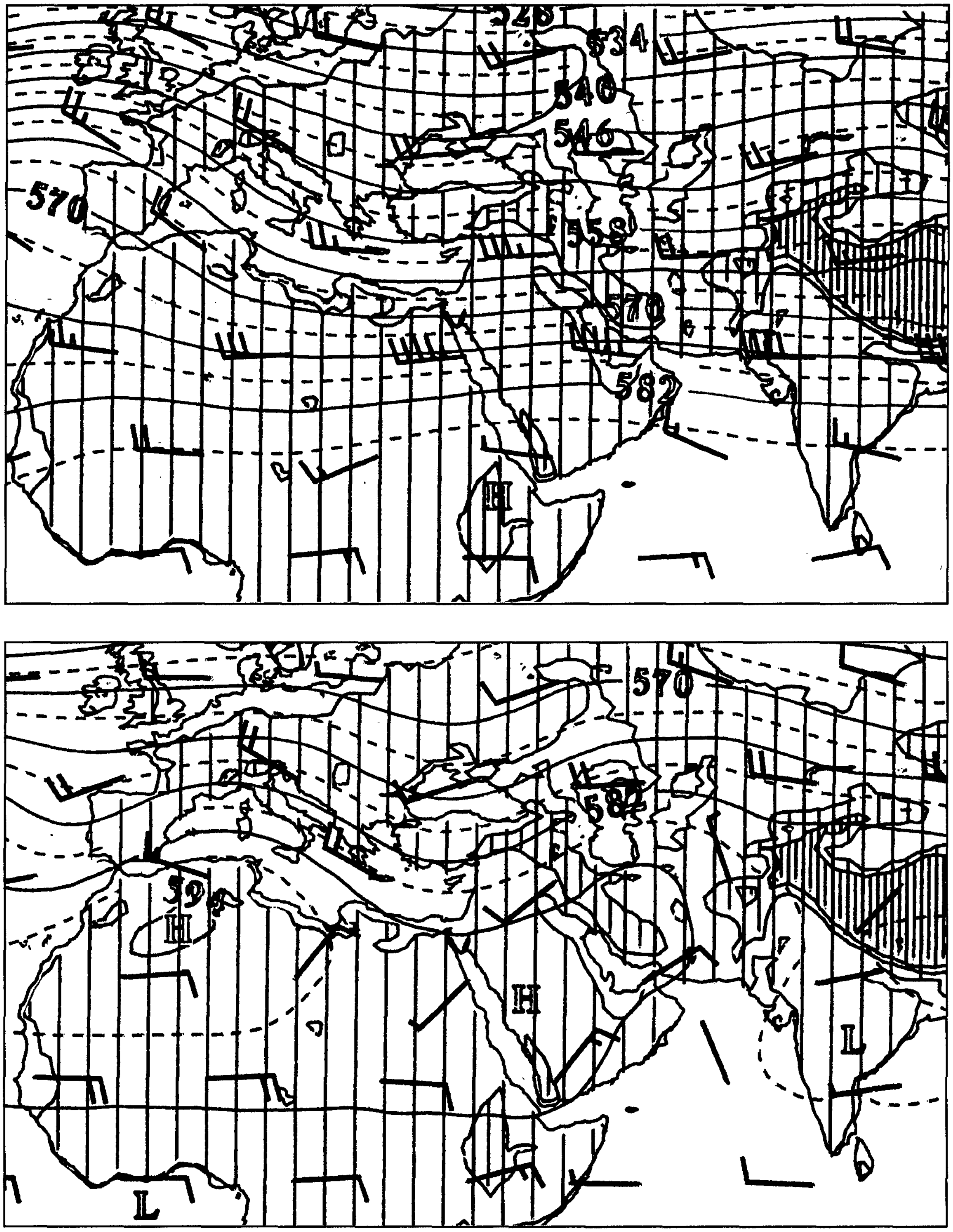


Figure 2-13. Mean January (top) and July (bottom) 500-mb Winds (knots) and Heights (meters). Local points of highest and lowest pressure are designated with "H"s and "L"s. Vector mean wind in 5-knot increments are shown. Winds less than 2.5 knots are depicted as a shaft with barbs. Contours of mean geopotential height (solid and dashed lines) in dekameters. Solid lines are labeled, dashed intermediate lines are unlabeled. Solid vertical lines indicate terrain elevations (tighter line spacing denotes higher elevation).

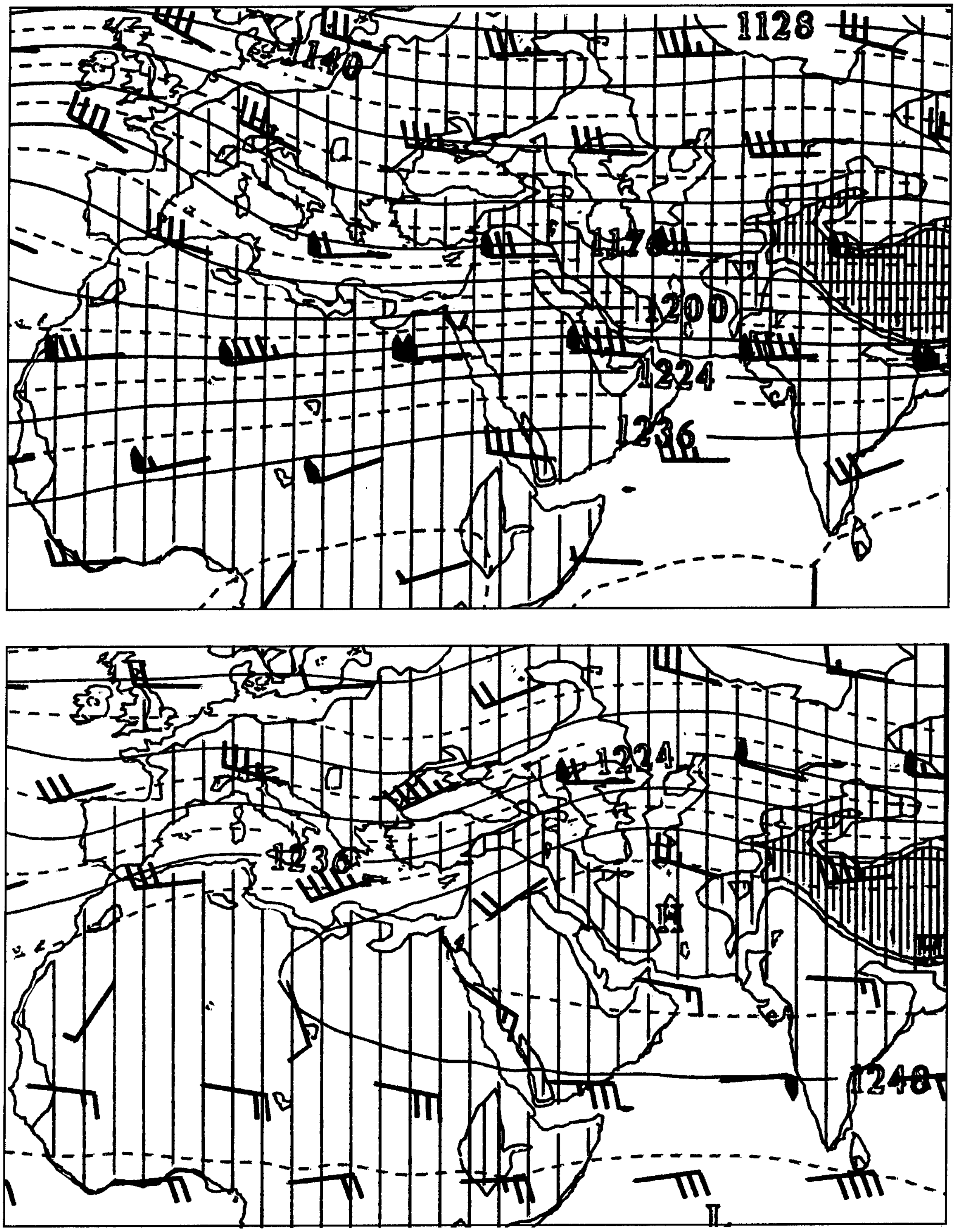


Figure 2-14. Mean January (top) and July (bottom) 200-mb Winds (knots) and Heights (meters). Local points of highest and lowest pressure are designated with "H"s and "L"s. Vector mean wind in 5-knot increments are shown. Winds less than 2.5 knots are depicted as a shaft with barbs. Contours of mean geopotential height (solid and dashed lines) in dekameters. Solid lines are labeled, dashed intermediate lines are unlabeled. Solid vertical lines indicate terrain elevations (tighter line spacing denotes higher elevation).

Mid-Latitude Low Pressure Systems and Fronts. An average of four low pressure systems a year enter the area through the Strait of Gibraltar. About three times during winter, fronts trailing from lows crossing Spain from the Bay of Biscay affect the region (see Figure 2-15). The Atlas Mountains prevent most of them from penetrate rating into the Sahara, but these systems can bring extensive low clouds and rain to the coast and snow to the mountains. On very rare occasions, a strong polar front manages to penetrate rate far into the Sahara. Although little moisture remains with the system, strong winds cause extensive sandstorms. In April 1986, a strong frontal system reached as far south as the Niger River, causing a duststorm that persisted for 86 hours at some locations. The great majority of depressions that affect the region do not originate in the Atlantic but develop over the Mediterranean as Genoa Lows.

Genoa Lows. From December through March, the Gulf of Genoa is a primary location for cyclogenesis, as airflow over the Swiss Alps leads to lee-side troughing over the northern Mediterranean. Transient disturbances intensify this troughing, leading to cyclogenesis. Almost 70 percent of all depressions affecting the Mediterranean originate in the Gulf of Genoa (52 a year: 16 in winter, 14 in spring, 10 in summer, and 12 in the fall; see Figure 2-15). The warm Mediterranean Sea supplies moisture to the developing lows, which normally track eastward toward Turkey. The trailing cold front normally extends as far as 200 NM inland over Northwest Africa. Though the fronts' features dissipate in the Atlas Mountains, lee side effects south of the mountains contribute to the development of Atlas Lows.

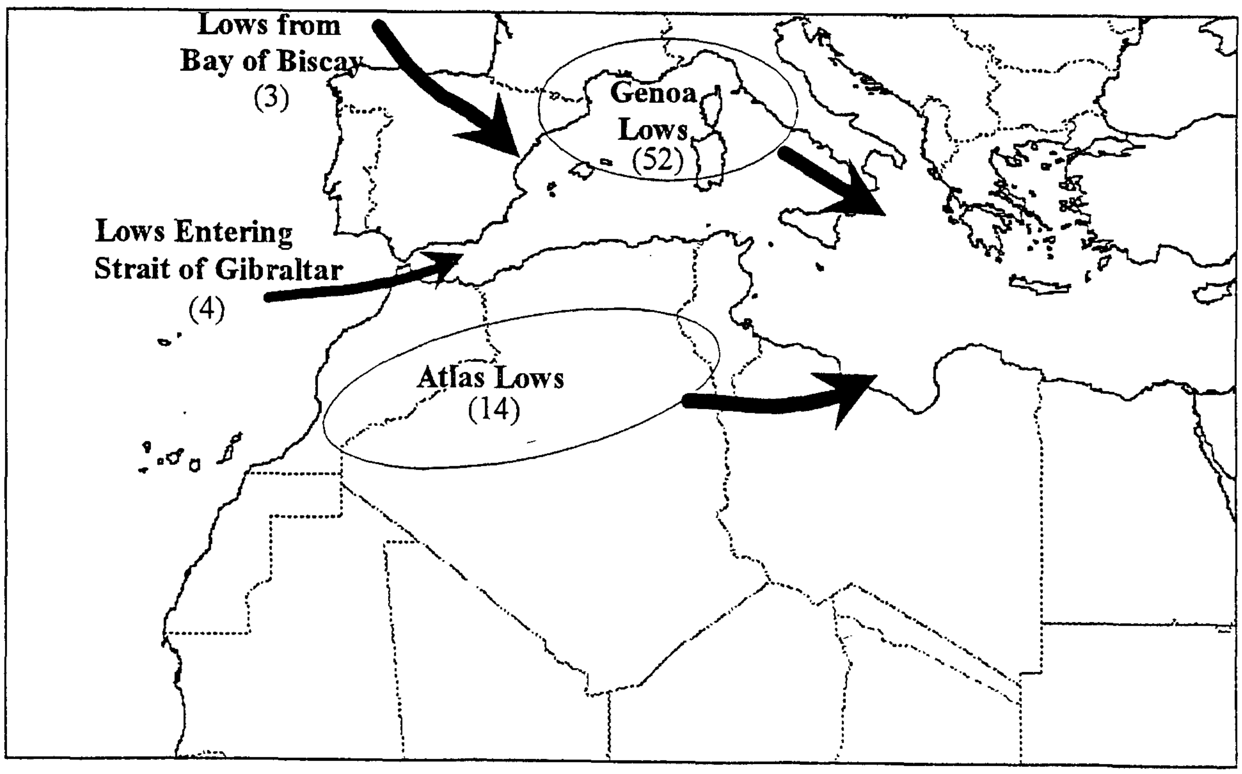


Figure 2-15. Primary Source Regions and Tracks of Depressions Affecting Northwest Africa. Average annual frequencies are in parentheses.

Atlas Lows. Atlas Lows form when a cold front trailing behind a mid-latitude low pressure system travels far enough south to cross the Atlas Mountains. When the winds behind the front are sufficiently strong, a dynamic trough is generated on the lee side of the mountains, and a closed low pressure center is established. Each year, an average of 14 Atlas Lows develop, accounting for 15-20 percent of the depressions that affect the region (see Figure 2-15). They develop most frequently from March through May, but they may occur any time of year. They usually develop in north-central Algeria near 30° N, 2° E. An upper-level trough lying west of the region generally steers Atlas Lows northeastward over the Mediterranean. These storms seldom penetrate rate very far into the Sahara without strong northerly flow and mid-level cold air support.

The subtropical jet (STJ) and polar jet (PJ) provide strong outflow and divergence aloft, and the low often deepens in the area between the jets. Jet stream interaction with Atlas Lows occurs most frequently between 25 and 30° N, nearest the mean position of the STJ. Figure 2-16 illustrates this PJ/STJ interaction and shows where Atlas Lows most commonly form (indicated by the "X").

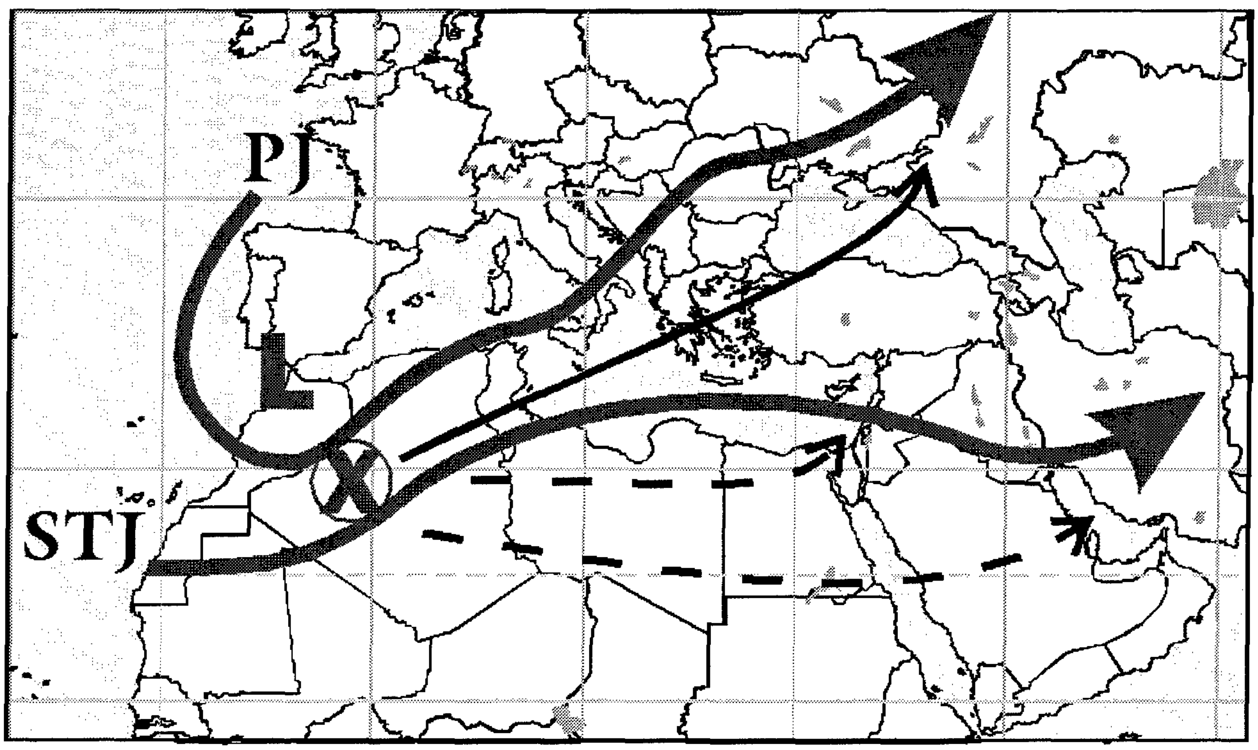


Figure 2-16. Typical Jet Stream Orientation during Formation of Atlas Lows. Heavy arrows indicate typical jet streams; light arrow indicates primary storm track; dashed arrows indicate secondary tracks.

The lows normally move northeast over the south-central Mediterranean, following the PJ/STJ axis. When sustained northerly flow persists for more than 3 days, however, the PJ and the mean Atlas Low track shift southward, and the lows move east across the northern Sahara (see Figure 2-17). Strong surface high pressure normally moves in behind the system, producing duststorms and sandstorms (see Harmattan).

Fronts can penetrate rate farther south as they travel east across Africa, primarily due to their increased distance from the Azores High. In extreme cases, fronts have reached 15° N across Mauritania, Mali, and Niger. Farther east, there is evidence they may have reached northern Nigeria, Cameroon, and the Central African Republic.

Moisture associated with Atlas Lows is normally limited to middle and upper levels. Before any rain reaches the surface, the lower layer must be saturated, but this only occurs with strong systems. When fronts do occasionally tap low-level moisture from the Atlantic, significant rainfall occurs along the west coast (from Mauritania to Guinea) and in the higher terrain. Coastal regions can receive 1-3 inches of rain, most commonly from stratiform clouds.

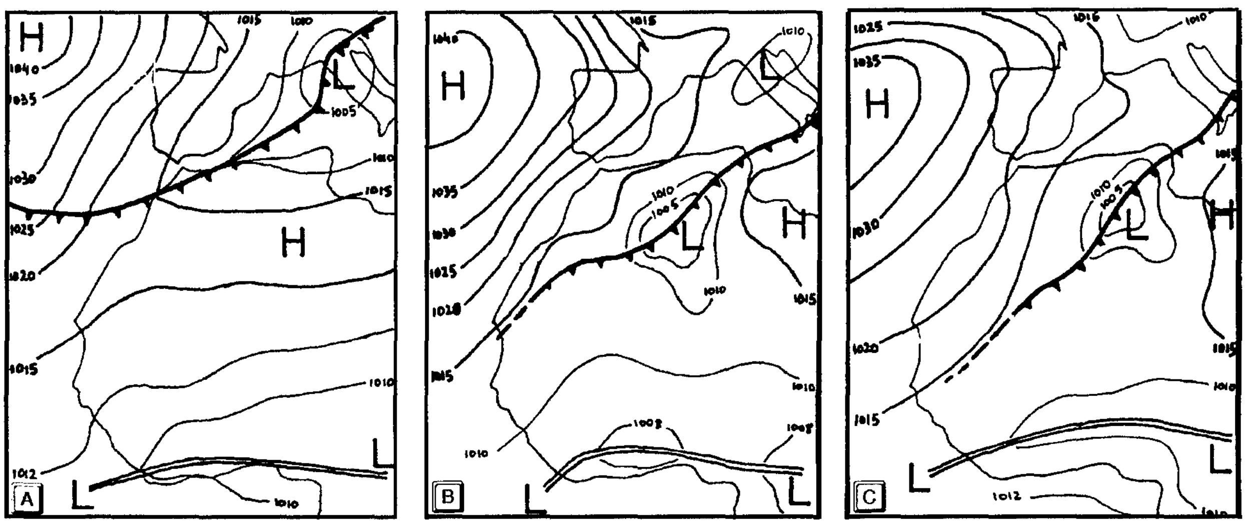


Figure 2-17. Atlas Low Development with Cold Front Reaching Sub-Sahara (Leroux, 1983). In (A), a cold front reaches Northwest Africa; the NETWC is shown over West Africa. In (B), the low develops along the existing front, with a strong high moving south behind it. In (C), the low travels east across the Sahara, and the weakening cold front reaches the Sub-Sahara.

African Waves. African (or Tropical) waves are disturbances that develop in the easterly flow north of the equator. They originate over southern Chad or Sudan at the 700-mb level from May to October. Although these waves usually stay south of 15° N, they can reach 30° N in midsummer, providing a significant amount of the scarce precipitation in the southern Sahara. African waves move east to west at 10-20 knots (5-10 degrees of longitude a day) across the continent and into the Atlantic. Successive waves can develop every 2-5 days. Wave lengths vary from 1,500 to 4,000 km. Figure 2-18 shows an idealized depiction of the structure of an African Wave.

Since moisture is limited, these disturbances produce little weather and seldom more than an increase in mid-level cloud cover before late June. Any convergence, cloud cover, and precipitation occur on the east side of the trough. However, by late July, the MTEJ is well-established. The NETWC's surface position is near 20° N, allowing more moisture to reach farther north and more cloudiness and rainfall to occur on the west side of the trough. In weaker troughs, mid-level winds are lighter than surface winds, but speeds of 30-40 knots are common in stronger waves. Closed circulations can develop at 700 mb and extend to the surface. These systems, called "West African Cyclones," can produce significant thunderstorms and precipitation. A small number of these generate hurricanes when they move into the Atlantic (see Figure 2-19).

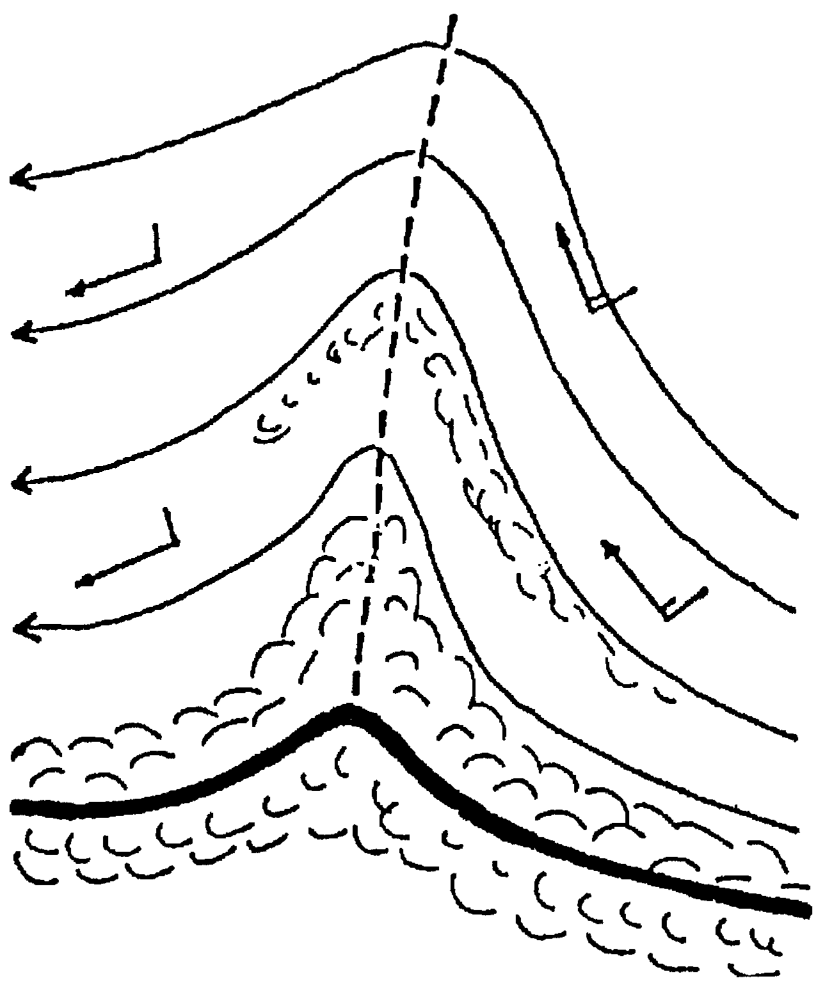


Figure 2-18. Basic Cloud and Wind Pattern of an African (Easterly) Wave (Leroux, 1983). The trough axis is shown by the dashed line. The solid line represents the 700-mb position of the NETWC .

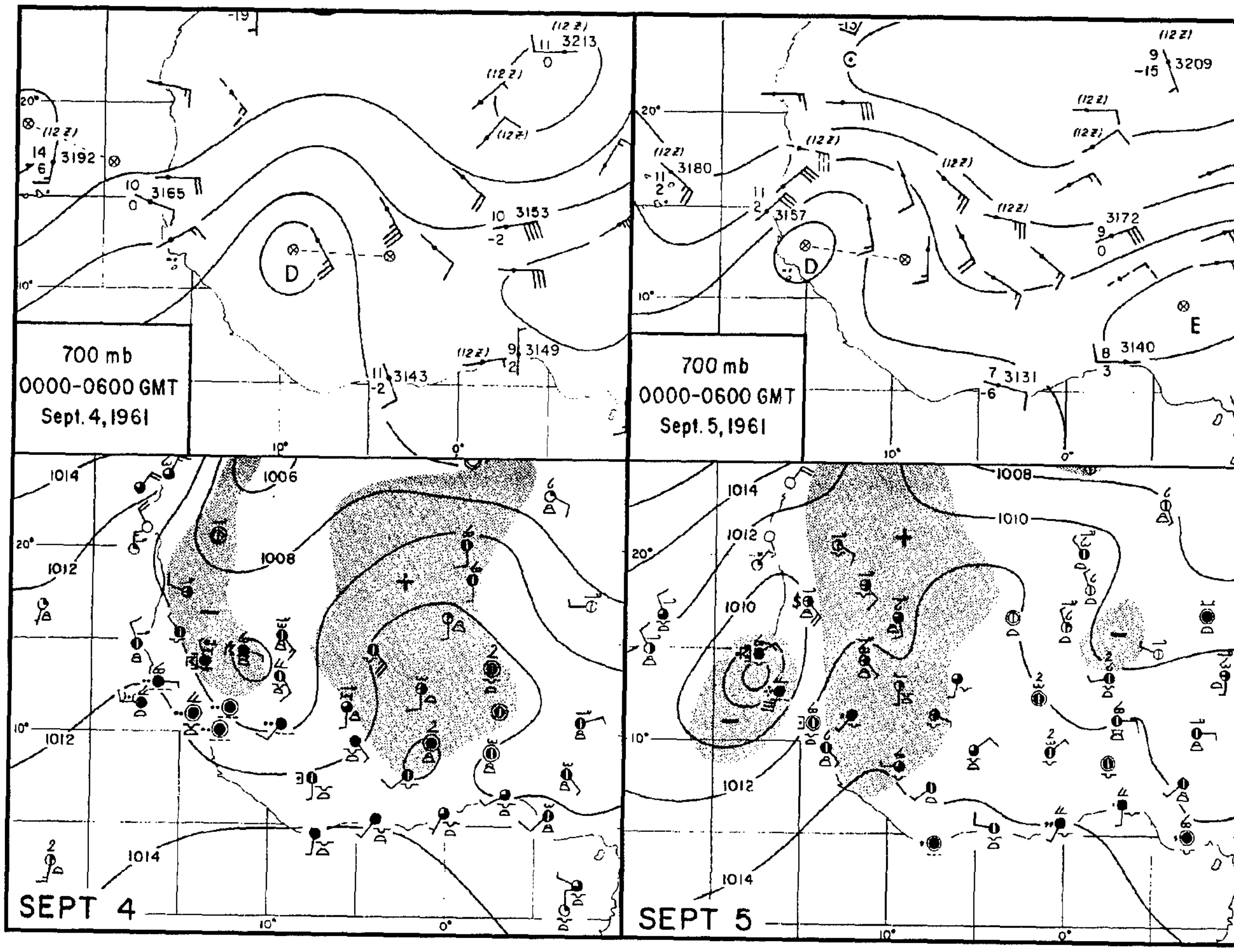


Figure 2-19. African Wave over West Africa Sept. 4-5, 1961, 700-mb and Surface. "X"s and dashed lines show the past 24-hour movement. The shading in the figure represents areas of 24-hour pressure change greater than 2 mb. The D on the 700-mb charts (top) marks the center of the closed low that later became Hurricane Debbie. It reached hurricane strength within 48 hours. The E shows another wave that became Hurricane Esther. The African wave off the coast has a closed low at the surface.

African Squall Lines. African (or Tropical) Squall Lines usually form over Sub-Saharan Africa between 5 and 15° N from June to September. When the NETWC lies unusually far north, these squall lines can bring brief, heavy showers to the southern fringes of the Sahara. The squall lines generally move westward at 20-35 knots, though extreme speeds reach 50 knots. They produce heavy downpours and strong winds with gusts up to 80 knots. The leading edge is often a sharply defined, north-south arc of convective cells in various stages of growth. African Squall Lines generally last about 12 hours. The local term for these systems is "tornadoes," but actual tornadoes are not associated with African Squall Lines.

African Squall Lines differ from mid-latitude squall lines in two significant ways: (1) The anvil cloud extends *behind* African Squall Lines; precipitation falling from the anvil cloud thus enhances mesoscale subsidence behind the system. (2) New convective squall lines develop *west* of the African Squall Line outflow boundary, making the system appear to continue for up to several days.

To the surface observer, these systems appear as a dark heavy band of cumulonimbus with a long roll cloud at the leading edge. Their typical length is 300 km. They occur most frequently 250-800 km south of the NETWC 's surface position, where the moist layer is 1,500-2,500 m deep. A solid deck of high-level altostratus trails the convection and usually produces light rain for up to several hours. Multiple squall lines can occur within 24 hours of each other at the same location.

Intense downdrafts and outflow boundaries occur beneath individual convective cells. Downdraft speeds average 20-30 knots over flat terrain, but they can be much higher, particularly near mountains. Cold downdrafts cause rapid temperature decreases and can raise large amounts of dust and sand; visibilities can be reduced to near zero. Brief, intense rainfall is common, but coverage is variable. Hail is common in higher terrain.

The Mid-Tropospheric Easterly Jet (MTEJ) enhances the development of African Squall Lines. This jet, located at about 650 mb, is colder than the environment and progressively sinks from east to west. When a wave develops in the airstream, the moist southwesterly flow is forced aloft; falling precipitation evaporates, cooling the jet more. If the MTEJ reaches the surface, a gust front forms, and the process becomes self-generating. Squall lines generally move west at the speed of the MTEJ. The convection zone develops between the cyclonic shear side of the MTEJ and the anticyclonic shear side of the Tropical Easterly Jet (TEJ).

The sequence of diagrams in Figure 2-20 shows the formation of an African Squall Line. Shearing along the NETWC (A) creates compression of the monsoonal flow below, leading to wave development (B). This causes increased airflow above and below the developing wave, further enhancing wave development (C). Further wave development usually requires an active jet stream aloft. The "blocking phase" shown in (D) often occurs in conjunction with an active MTEJ. When the mid-level flow breaks through the NETWC and reaches the surface (E), the easterly flow is forced to spread north and south, forming the north-south arc of the actual thunderstorm line. Westerly flow is forced aloft, producing heavy rain and thunderstorms. Easterly flow drives the storms west, as individual thunderstorms tend to move with the low- to mid-level synoptic flow.

Several factors may cause African Squall Lines to dissipate or prevent their formation altogether. African Squall Lines frequently diffuse around coastal areas, where temperature inversions prevent rising air from reaching the Lifting Condensation Level. Dissipation also occurs if the supply of low-level moisture is cut off or if the MTEJ does not reach the surface. A squall line may dissipate or only produce light rain upon entering an area of recent thunderstorms, due to mixing of the lowest layers of the atmosphere. However, some squall lines will regenerate after passing such an area.

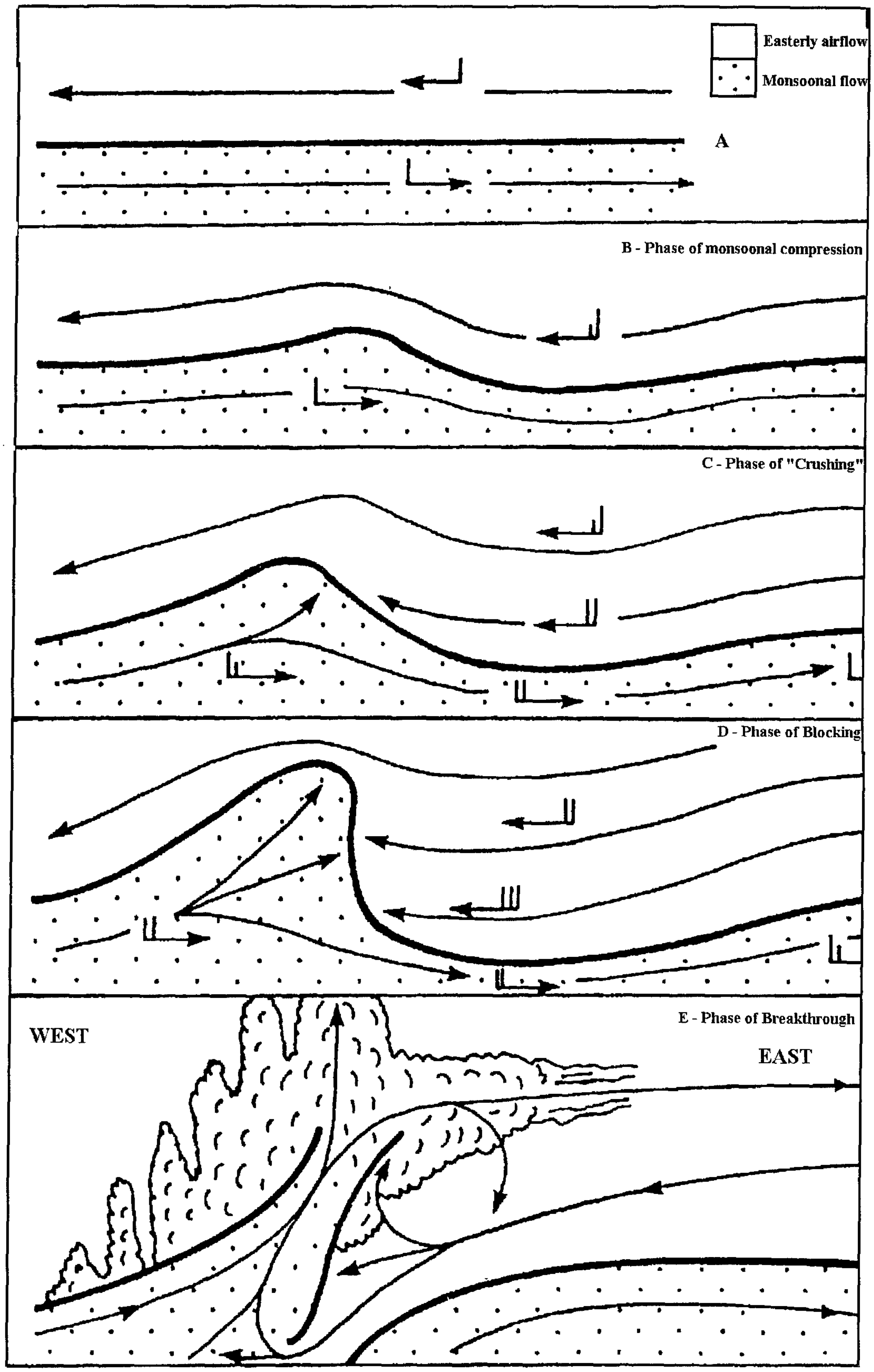


Figure 2-20. **Vertical Cross-Section Showing the Formation of an African Squall Line (Hayward, 1987).**

Duststorms/Sandstorms. Under the right conditions, duststorms can be dominant features in and near the Sahara. Duststorms carry suspended particles over long distances, often reducing visibility to less than 10 meters. Wind direction, amount of particulate matter, duration, and season vary by locality. In the heart of the Sahara, duststorms occur almost daily from March through September. Large-scale duststorms often persist for 1 or 2 days before a frontal passage or with a synoptic-scale squall line. Mesoscale squall lines may reduce visibility to less than 1,000 m for several minutes to an hour. Sandstorms differ from duststorms only in the size of the suspended particles. Sand, being heavier, is seldom raised more than 1-2 m above the ground, and the particles settle quickly.

Strong pressure gradients associated with mid-latitude surges and tropical disturbances generate the winds needed to produce synoptic-scale duststorms. Most large-scale dust clouds move toward the west and the equator. Those in the Sahara are elongated plumes typically 1,000 km long and 200 km wide.

Winds of 15-20 knots are sufficient to lift dust and sand. The mean threshold value is 17 knots, but speeds as low as 10-12 knots can produce duststorms. A pressure gradient of only 4 mb per 10 degrees of latitude is needed to induce dust-laden surface winds. A pressure gradient of 6 mb per 10 degrees of latitude produces widespread duststorms 50 percent of the time.

The origin and nature of duststorms depend on general synoptic conditions, local surface conditions, and seasonal/diurnal considerations, as discussed below.

• Synoptic conditions favorable to the development of duststorms/sandstorms:

The Saharan High (Harmattan winds). The Saharan High normally intensifies during winter, and drives the persistent northeasterly winds known as the Harmattan (discussed below). These northeast winds lift dust and sand and spread it south and west. Stagnant air aloft provides little ventilation to remove the dust. This high sometimes produces severe and widespread duststorm activity that is extremely difficult to forecast.

Active cold fronts and depressions. In the northern Sahara, extensive, long-lasting duststorms can develop within the strong surface winds accompanying Atlas Lows or cold fronts trailing from Mediterranean depressions. These duststorms affect large areas and may persist for 1 or 2 days as the systems traverse the area.

Convective activity. Convective downdrafts commonly reach speeds needed to produce short-lived duststorms and sandstorms. These occur in the southern Sahara during July and August, when the NETWC reaches its northernmost point. Visibilities can be greatly reduced within minutes. Duststorms created by convective downdrafts are frequently called *Haboobs*.

• Local surface conditions favorable to the development of duststorms/sandstorms:

Soil type and condition control the amount of particulate matter that can be raised into the atmosphere. Dry sand or silt, for example, is easily lifted by 10-15 knot winds. Fine dust, salt, or silt can be suspended for weeks and travel hundreds, even thousands, of kilometers; haze is a persistent feature of the deserts. The Harmattan blows dust from the Sahara south and into the Atlantic. On rare occasion, the particles can precipitate back to the surface as "mud rain." Figure 2-21 shows the primary Saharan dust trajectories across western Africa.

• Seasonal considerations relevant to the development of duststorms/sandstorms:

Winter. The northeasterly winds of the Harmattan frequently spread dust and haze across the southern and western portions of the area. In the north, widespread duststorms develop with Atlas Lows and along frontal boundaries trailing from Mediterranean depressions. Synoptic-scale winds of only 10-15 knots can lower visibility to below 5,000 m over large areas for up to 12 hours.

Summer. In the south, convective downbursts generate the strong winds needed for duststorm development. When winds are light, dust devils occur frequently during the hot afternoons throughout the Sahara. Late spring frontal systems and Atlas Lows produce widespread duststorms in the north.

• Diurnal considerations relevant to the development of duststorms/sandstorms:

Daytime. Daytime heating produces turbulent mixing in the lowest layers. Hot, dry winds transport dust aloft to the base of the large-scale subsidence inversion. Persistent dryness allows dust to reach 3,000 m MSL, where it can remain suspended for days or weeks.

Nighttime. Cooler surface temperatures create stable conditions in the surface layer. Turbulent mixing is minimized, and the dust settles beneath the inversion layer throughout the night. Visibilities improve to 6-10 km during the night; they are best between 2000 and 0600 local, when the temperature inversion produces light surface winds.

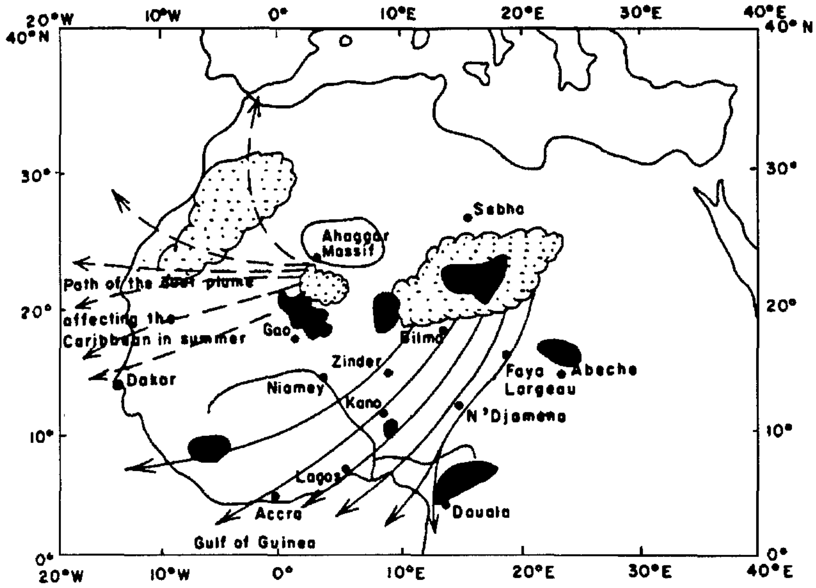


Figure 2-21. Saharan Dust Trajectories across Western Africa (Omotosho, 1989). The main sources of dust are shaded. Darkened areas in the figure represent land above 2,000 meters.

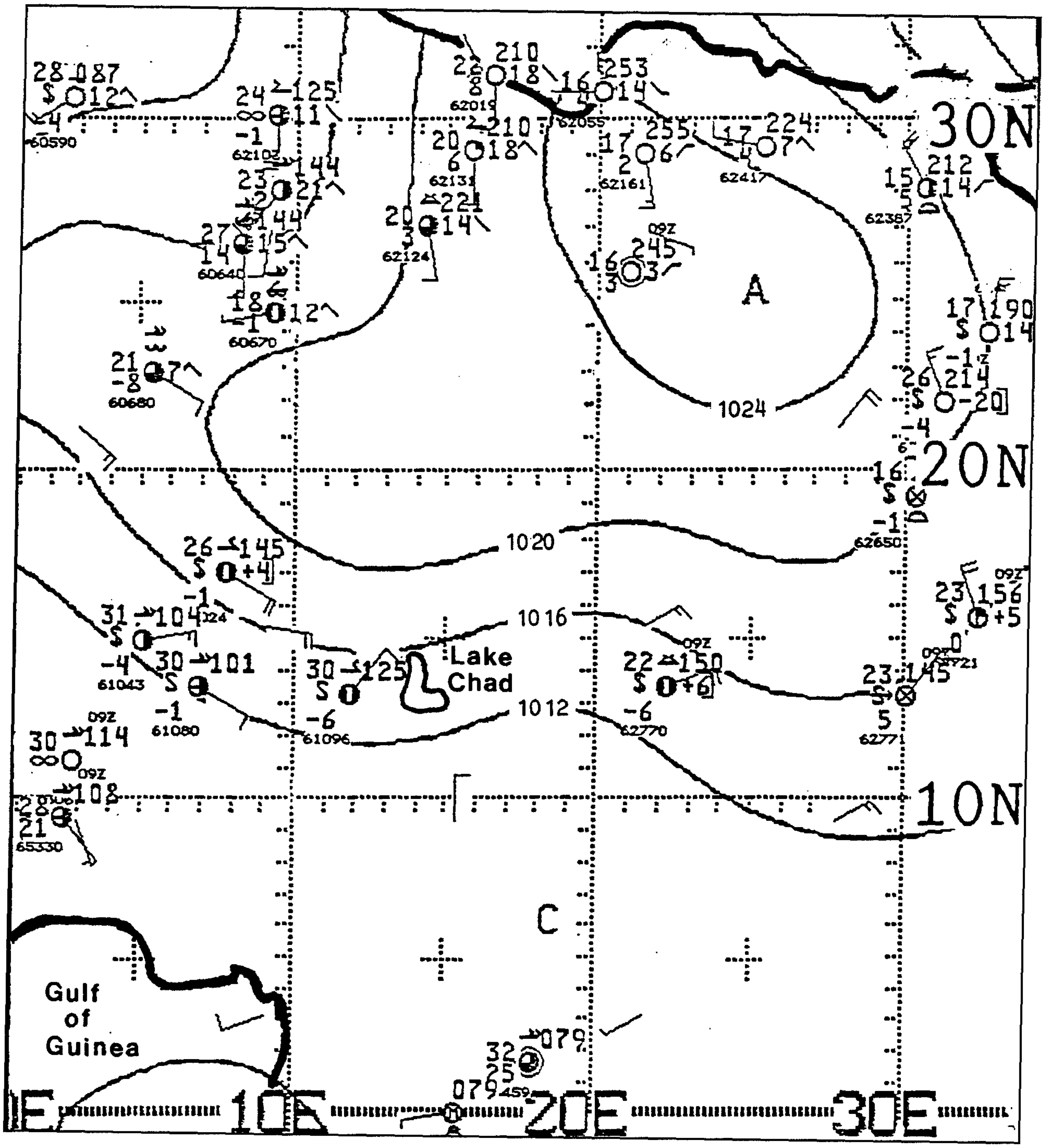


Figure 2-22. Surface Chart of Harmattan-Produced Duststorm over North Africa March 6, 1991. Wind barbs without station data are satellite-derived. Note the dusty conditions associated with the southern quadrant of the anticyclone.

Harmattan/Harmattan Haze. The Harmattan is a dry, dust-bearing northeasterly-to-easterly wind that originates in the Sahara and causes hot, dusty conditions south of the Sahara. The northeasterlies, though possible any time of year, are most persistent from November through March, when the Saharan High is strongest. Severe outbreaks of the Harmattan also occur behind strong cold fronts and Atlas Lows; winds reach 30-45 knots. Turbulent surface mixing produces a thick dust haze that normally reaches 1,000 feet (300 m) AGL, but it can reach 11,000 feet (3,600 m) MSL and extend southward to 5° N. Visibility is generally less than 6,000 m, and values as low as 200 m have occurred. Normally, three to five severe Harmattan outbreaks occur from January to May, causing severe duststorms with extremely low visibility and high winds for 12-24 hours. The synoptic chart in Figure 2-22 shows a duststorm associated with the Harmattan over North Africa.

Harmattan Haze occurs as dust reaches the NETWC and is forced aloft, with the base of the haze layer often reaching 3,000-5,900 feet (900-1,800 m). It can be present year-round and persist for extended periods. Horizontal visibilities at the surface increase south of the NETWC as the dust layer is forced aloft, but slant-range visibilities are lower. Horizontal visibilities are usually 5-10 km; slant-range only 2-5 km.

Chilis. Duststorms and sandstorms are not nearly as frequent along the extreme northern Sahara and the Mediterranean as they are farther south, but this area does experience hot, dry southerly winds known locally as *chilis*. The broader term for these winds is the SIROCCO. Strong southerly flow ahead of an Atlas Low often spawns a chili. The Atlas Mountains prevent most of the dust associated with chilis from reaching the coast, but coastal regions experience extreme dryness and heat under the influence of chilis, with extensive dust and haze layers aloft. Chilis occur most frequently during late spring and early summer over Algeria and Tunisia; about five chilis a year occur, each lasting about 24 hours. Along the Atlantic coast of Morocco, a similar east or southeasterly desert wind is known as the *chergui*. It is very dry and dusty, being hot in summer, cold in winter. Cherguis occur primarily from February through September with peak occurrences from mid-July to late August. This wind is possible when high pressure sets up over the Mediterranean and isobars are oriented roughly parallel to the coastline.

Dust Devils. The great temperature difference between the hot sand surface (which may reach 77° C) and the relatively cooler air causes very unstable conditions that trigger dust devils. While dust devils are much smaller and less violent than tornadoes, they are destructive. Wind speeds within dust devils are generally between 15 and 30 knots, but winds strong enough to break windows and overturn tents have been reported. Pilots landing at superheated runways should scan the area 3-5 km upwind to preclude the possibility of entering dust devils at low altitudes or near stall speeds. Dust devil diameters range from 10 to 295 feet (3 to 90 m), averaging around 20 feet (6 m). Although most reach 250 feet (75 m) high, dust has been observed at 3,000 feet (900 m). Dust devils move at about 10 knots and normally do not last longer than 20 minutes, but some have persisted for several hours. Visibilities are near zero in the vortex.

Land and Sea Breezes. Differential surface heating generates these diurnal phenomena along most coastal areas of Northwest Africa, but they are by far more pronounced along the Mediterranean coast than the Atlantic. Figure 2-23 illustrates the "common" land/sea breeze circulation, which assumes calm conditions, no topographic influences, and a uniform coastline. Land/sea breezes normally reverse at dawn and dusk. The marine boundary layer rarely extends above 3,280 feet (1,000 m) AGL or beyond 30 km inland unless modified by synoptic flow.

Along the Mediterranean coast during spring and fall, the sea breeze normally begins in early afternoon and continues until 1900 LST. The sea breeze is more prominent from June to August, and it normally begins by 1000 LST. Speeds average between 10 and 15 knots, augmenting the northeasterly flow. Downslope flow, especially strong when mountain tops are snow-covered, enhances the land breeze, which prevails during winter. The land/sea breeze circulation is much less pronounced along the Atlantic coast, where the strong influence of the Azores High produces northeasterly surface winds most of the year. These winds, by parallelling the coast and preventing Atlantic moisture from advecting inland, contribute to the dry conditions of the Sahara.

High terrain near the coastline modifies the land/sea breeze in several ways. Uplands deflect surface winds, and mountain circulation accelerates the land breeze over water. Elevated coastal topography produces steep nighttime temperature gradients. Figure 2-24 shows the land/sea breeze circulation with onshore gradient winds and coastal mountains, a common situation along Northwest Africa's Mediterranean coast. Coastal configuration also affects land/sea breezes: coastlines perpendicular to landward synoptic flow maximize sea breeze penetration, while coastlines parallel to the flow minimize it.

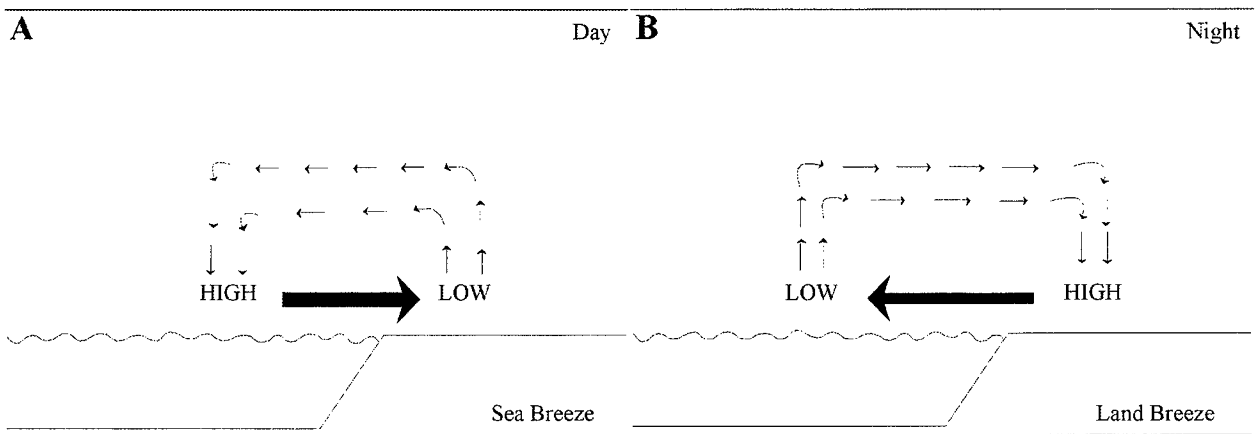


Figure 2-23. The Sea and Land Breezes. Sea (A) and Land (B) flows intensify in proportion to daily heat exchanges between land and water. Thick arrows depict the surface flow.

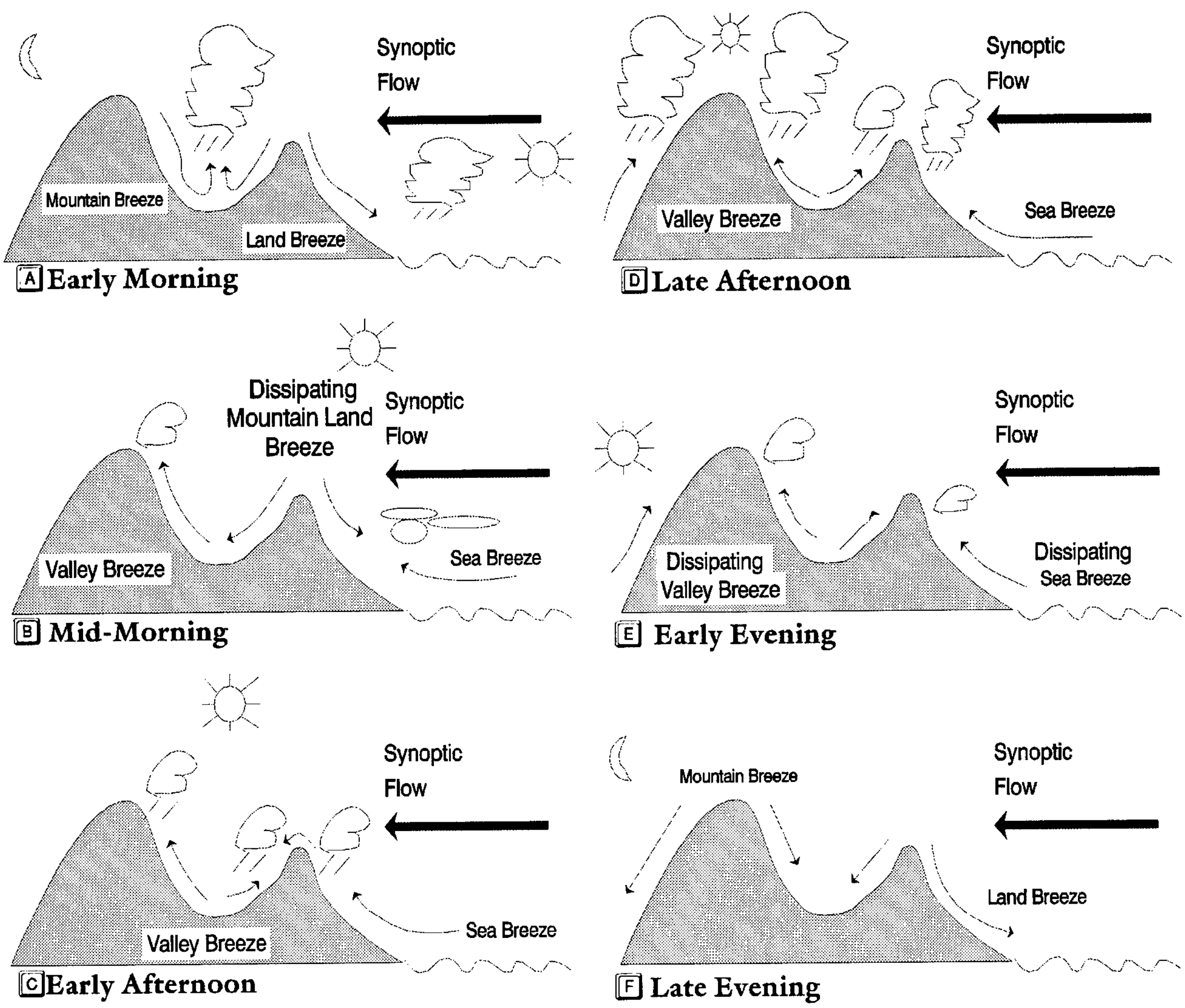


Figure 2-24. Land/Sea Breeze with Onshore Gradient Flow. Onshore gradient flow accelerates orographic lifting by day and produces localized convergence over open water during early morning. By mid- to late afternoon, the sea breeze is well established, and convection moves inland over the ridge tops.

Winds in the Strait of Gibraltar. Winds are channelled through the narrow Strait of Gibraltar, leading to unique, often turbulent wind regimes in the immediate vicinity (especially on the Spanish side of the Strait). Local names for some of these winds are listed below:

Ponientes. Westerly winds usually accompanied by fair weather.

Levanters. Easterlies that are very persistent during summer and accompanied by clear skies. During spring and fall, levanters are associated with Atlas Lows and often bring heavy rain and thunderstorms.

Vendavales. Southwesterly winds preceding Atlantic depressions; associated with heavy rain and thunderstorms.

Contrastes. Local term for the very turbulent conditions when surface winds blow in opposite directions at very short distances from each other. These conditions occur east of the Strait in winter, when winds are often easterly off the Spanish coast but westerly off the Moroccan coast.

Mountain-Valley and Slope Winds. These terrain-induced winds (shown in Figure 2-25) develop under fair skies with light and variable synoptic flow. Valley winds tend to be stronger than slope winds and can override their influence. Mountain-Valley winds are produced in response to the pressure gradient between a mountain valley and a plain outside the valley. Air within the valley heats and cools faster than air over the plain. Daytime up-valley winds are strongest, averaging 10-15 knots between 650 and 1,300 feet (200 and 400 m) AGL; nighttime down-valley winds average only 3-7 knots at the same level. Peak winds occur at the valley exit. Deep valleys develop more nocturnal cloud cover than shallow valleys because nocturnal convergence is stronger. The mountain-valley circulation can reach 6,600 feet AGL (2,000 m), but the depth of the circulation is determined by the valley's depth and width, the strength of prevailing winds in the mid-troposphere (stronger winds produce a shallower circulation), and the breadth of microscale slope winds.

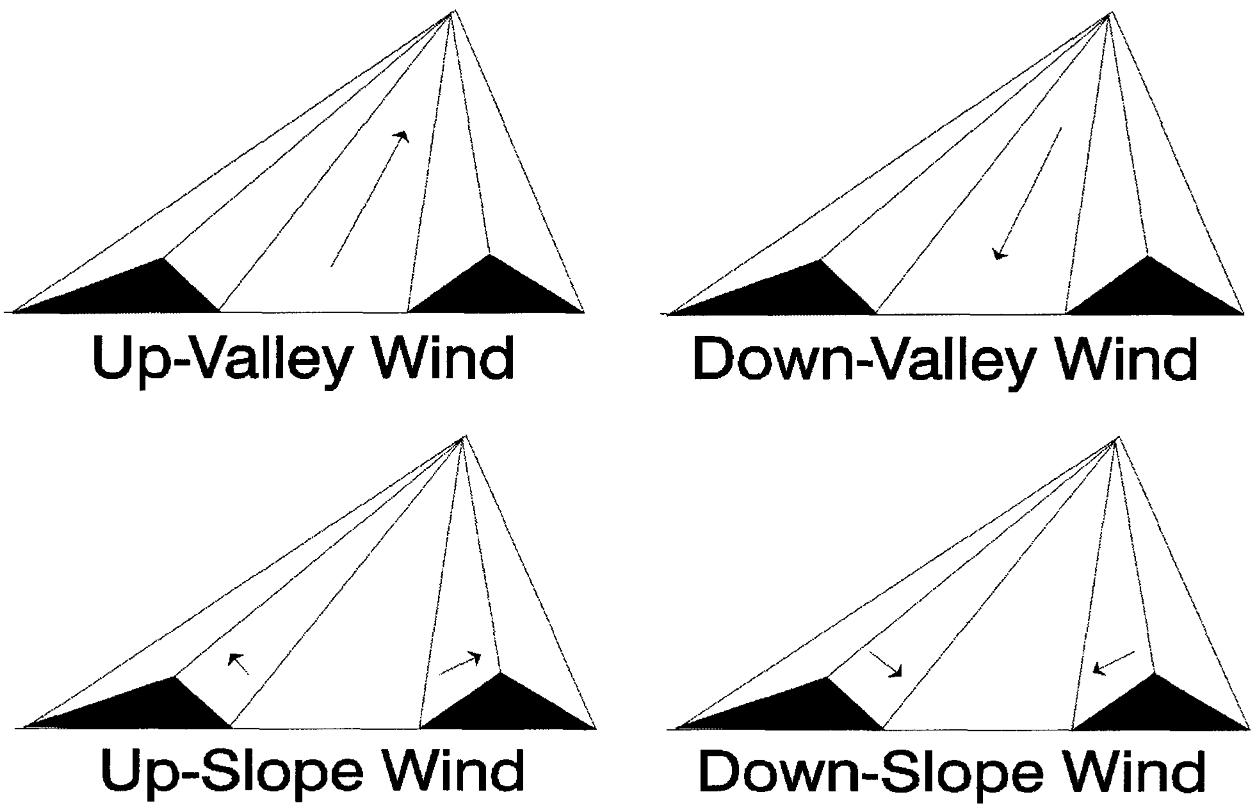


Figure 2-25. Mountain-Valley and Slope Winds (Whiteman, 1990). The arrows indicate direction of terrain induced winds.

Slope winds develop along the surface boundary layer and seldom extend beyond 500 feet (150 m) AGL. Mean daytime upslope wind speeds are 6-8 knots; mean nighttime downslope wind speeds are 4-6 knots. Steep slopes can produce higher speeds, and winds from a large mountain can disrupt the winds of a smaller one. Downslope winds are strongest during winter, while upslope winds are strongest in summer, especially on slopes facing the sun. In some locations, cold air can be dammed up against a plateau or in a narrow valley; when sufficient air accumulates, it spills over in an "air avalanche" of strong winds. Figure 2-26 shows the life cycle of typical mountain-valley and slope wind circulations.

Mountain inversions develop when cold air builds up along wide valley floors. Cold air descends at 8-12 knots but loses momentum when it spreads out over the valley floor. Wind speeds average only 3 knots by the time the downslope flows from both slopes converge. The cold air replaces warm, moist valley air at the surface and produces a thin smoke and fog layer near the base of the inversion. Sunrise initiates upslope winds by warming the cold air trapped on the valley floor.

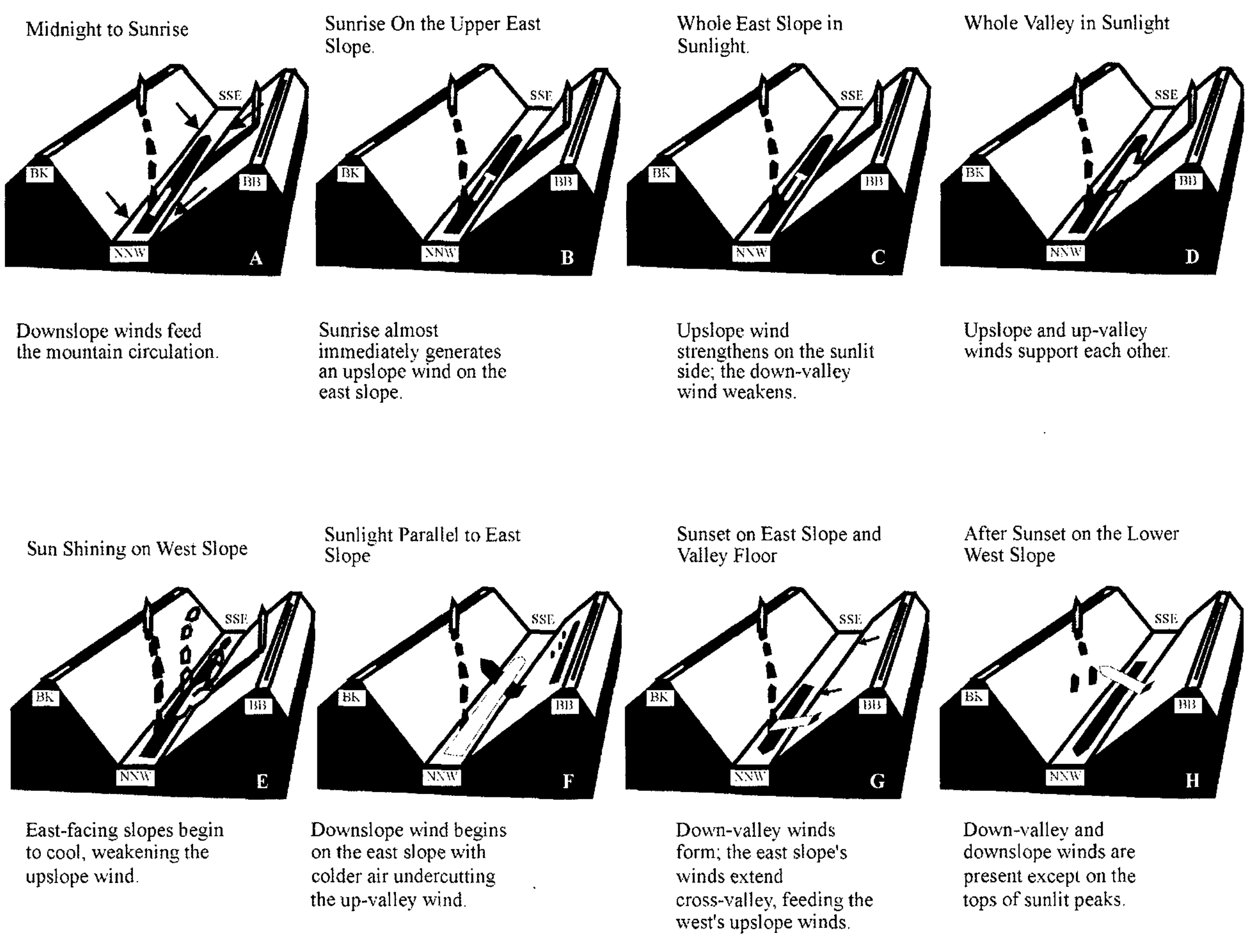


Figure 2-26. Diurnal Variation of Slope and Valley Winds (Barry, 1981). Dark arrows show ground-level flow; light arrows above-ground flow.

Mountain Waves develop when air at lower levels is forced over the windward side of a ridge. Criteria for mountain wave formation include sustained winds of 15-25 knots, winds increasing with height, and flow oriented within 30 degrees of perpendicular to the ridge. Wavelength and amplitude are dependent on wind speed and lapse rate above the ridge. Light winds follow the contour of the ridge, with little displacement above and rapid damping beyond. Stronger winds lift air above the stable inversion layer, and the displaced air can reach the tropopause. Downstream, the wave propagates an average distance of 50 times the ridge height. Rotor clouds form when a core of strong wind moves over the ridge, but the elevation of the core does not exceed 1.5 times the ridge height. The strongest turbulence is observed in the vicinity of rotor clouds. Figure 2-27 shows a fully developed lee-wave system.

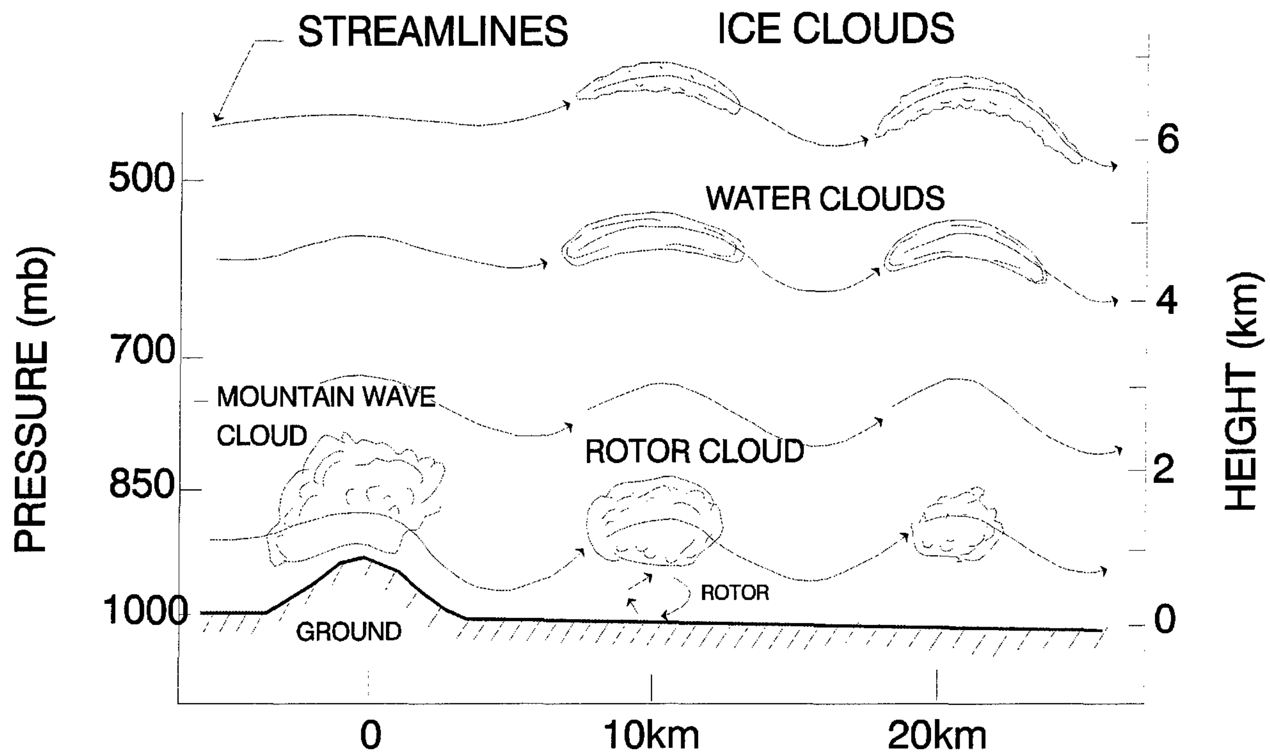


Figure 2-27. Fully Developed Lee-Wave System (Wallace and Hobbs, 1977). The circular arrows around the rotor cloud indicate the turbulence associated with lee-wave systems. Clouds may not always develop in dry regions, though waves may still be present.

Wet-Bulb Globe Temperature (WBGT). The WBGT provides values that can be used to calculate the effects of heat stress on individuals. WBGT is computed using the formula:

$$WBGT = 0.7WB + 0.2BG + 0.1DB$$

where WB = wet-bulb temperature
BG = Vernon black-globe temperature
DB = dry-bulb temperature

WBGT (° C)	Water Requirement	Work/rest Interval	Activity Restrictions
32-up	2 quarts/hour	20/40	Suspend all strenuous exercise.
31-32	1.5-2 quarts/hour	30/30	No heavy exercise for troops with less than 12 weeks hot weather training.
29-31	1-1.5 quarts/hour	45/15	No heavy exercise for unacclimated troops, no classes in sun, continuous moderate training 3rd week.
28-29	.5-1 quart/hour	50/10	Use discretion in planning heavy exercize for unacclimated personnel.
24-28	.5 quart/hour	50/10	Caution: Extremely intense exertion may cause heat injury.

Figure 2-28. WBGT Activity Guidelines. The physical activity guidelines are based on those used by the three services. Note that the wear of body armor or NBC gear adds 6° C to the WBGT, and activity should be adjusted accordingly.

A complete description of the WBGT and the apparatus used to derive it is given in Appendix A of TB MED 507, *Prevention, Treatment and Control of Heat Injury*, July 1980, published by the Army, Navy, and Air Force (see Figure 2-28).

Figure 2-29 gives mean daily high WBGTs for January and July. For more information, see USAFETAC/TN—90/005, *Wet Bulb Globe Temperature, A Global Climatology.*

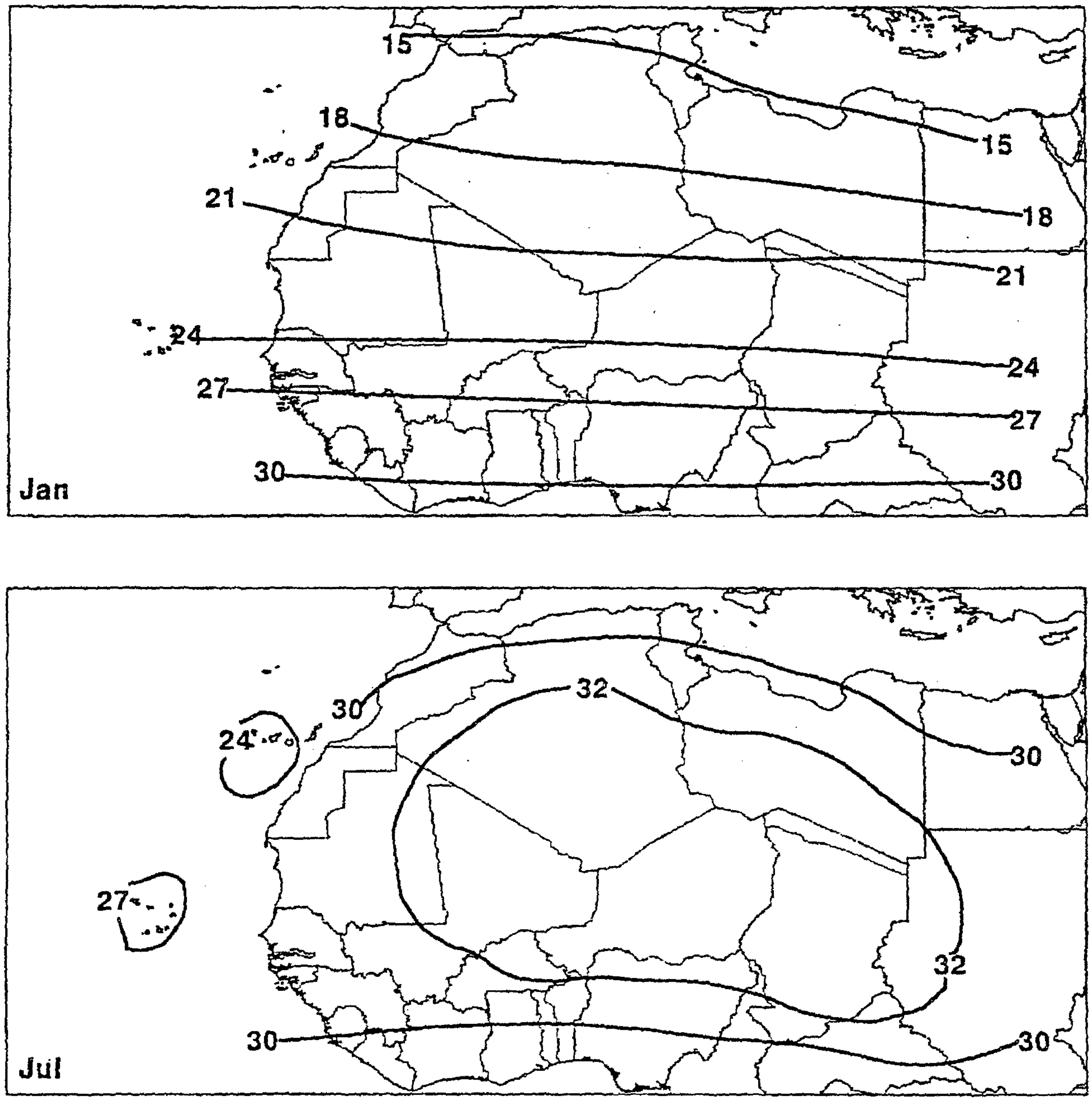
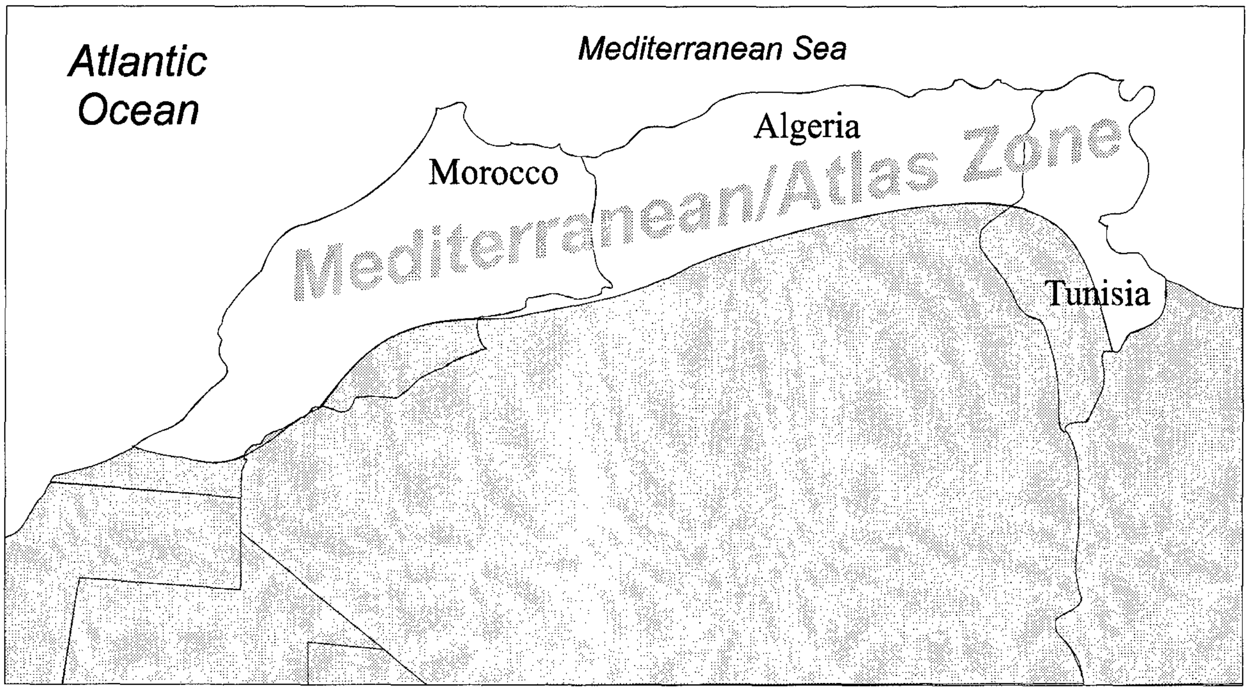


Figure 2-29. Mean Maximum WBGT during January (top) and July (bottom). The isopleths show areas of activity restriction in Northwest Africa increase from "use caution" in January to "suspend all strenuous exercise" in July.

Chapter 3

MEDITERRANEAN/ATLAS ZONE

This chapter describes the geography, major climatic controls, special climatic features, and general weather by season for the Mediterranean/Atlas Zone of Northwest Africa. It consists of Algeria and Tunisia from the Mediterranean coast through the Atlas Mountains and nearly all of Morocco from the Atlantic Coast eastward through the Atlas Mountains.



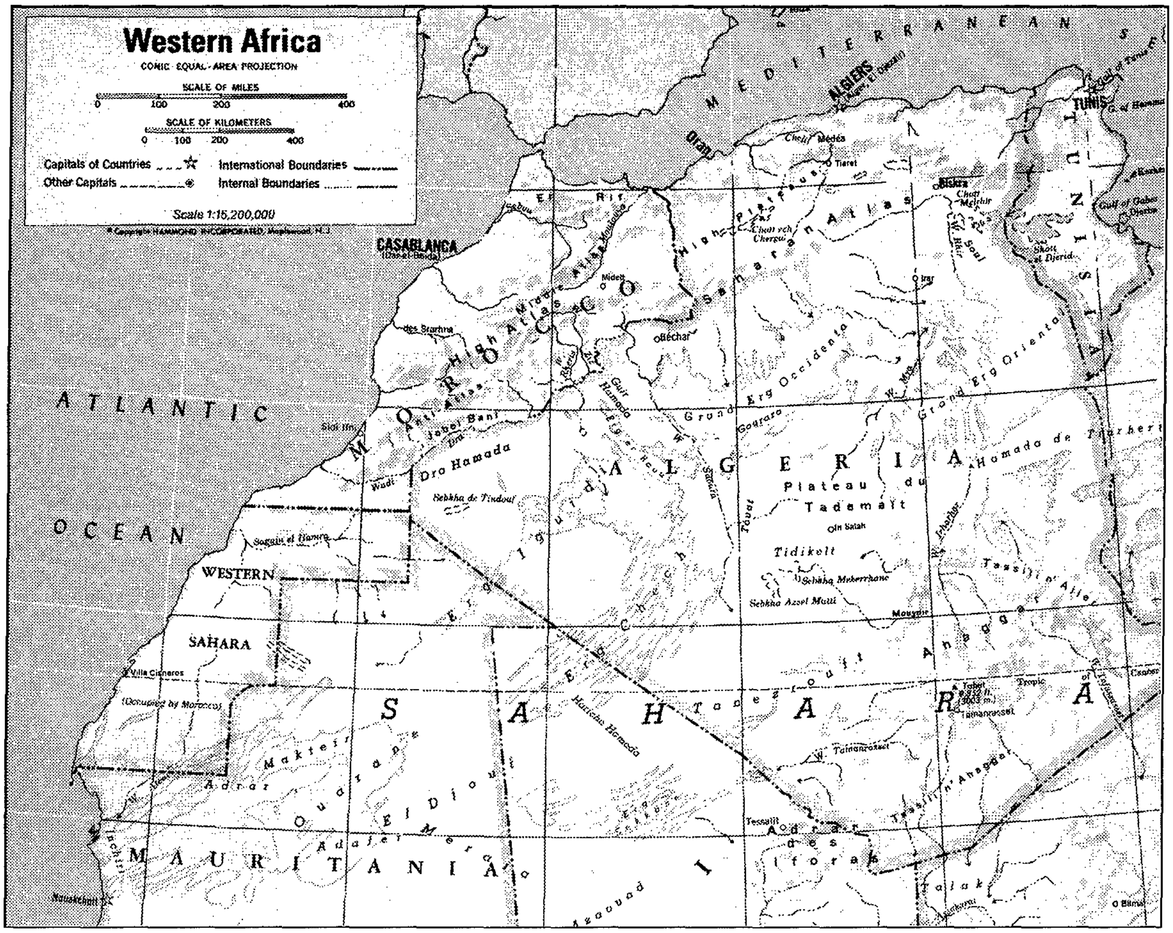


Figure 3-1. Topography of the Mediterranean/Atlas Zone.

Boundaries. The Atlantic Ocean borders the Mediterranean/Atlas Zone on the west and the Mediterranean Sea borders the region on the north and east. The southern border divides the Mediterranean/Atlas Zone from the Saharan Zone based upon mean annual precipitation. The area included in the Mediterranean/Atlas Zone has annual mean precipitation greater than or equal to 125 mm; less than 125 mm is part of the Saharan Zone to the South. This puts the southern border south of the Atlas Mountains, extending from the Tunisia-Libya border at about 32° N northwestward to about 34°30' N, 7°E. Then it extends southwestward to the Atlantic Ocean on the coast of Morocco at about 28° N (see Figure 3-1).

Major Terrain Features. The Atlas Mountains dominate the terrain of the Mediterranean/Atlas Zone as several distinct ranges that stretch about 2,400 km southwest-northeast across the Maghreb region of Africa (northern Algeria, Tunisia, and Morocco). A smaller range, the Er Rif, lies parallel to the Mediterranean coast in northern Morocco. A high plateau or steppes called the Hauts Plateaux (High Plateau) extends from eastern Morocco across northern Algeria. The Atlas mountains encircle this plateau. Except for narrow, fertile coastal plains, the mountains and plateaus dominate the terrain of the Mediterranean/Atlas Zone of Northwest Africa.

Morocco has the broadest plains and highest mountains with an average height above sea level of 2,600 feet (800 meters) MSL. The highest range of the Atlas Mountains, the Haut Atlas (High or Grand Atlas) lies in southwestern Morocco with its highest peak, Mount Toubkal, at 15,137 feet (4,165 meters) MSL. The next highest mountains are the Moyen (Middle) Atlas Mountains, which rise to 11,000 feet (3,350 meters) MSL through the center of the country. South of the High Atlas, and parallel to them, are the Anti-Atlas Mountains. With heights to 6,750 feet (2,060 meters) MSL, the Anti-Atlas Mountains extend to the Atlantic coast of Morocco. The Er Rif in northern Morocco has mountains reaching as high as 8,055 feet (2,456 meters) MSL. Rocky plateaus at about 3,000 feet (900 meters) MSL cover nearly one-half of Morocco. A broad coastal plain between the Atlantic Ocean and the Er Rif and Atlas ranges contains the most fertile land in Morocco and houses most of the population.

In northern Algeria, the coastal plain, the Atlas Mountains and high plateau dominate the terrain. The Atlas Mountains divide into two chains with the high plateau or steppes between them. Between the Atlas mountains and the Mediterranean Sea lies a narrow coastal plain known as the Tell (Arabic for "hill"). This fertile region extends inland 80-190 km from the coast and is the most heavily populated part of Algeria. Hills and ridges that terminate in high cliffs over looking the sea line the coastline of the Tell. Large coastal plains in some areas, such as those in the vicinity of Algiers, Oran, and Annaba, also are part of the Tell. The Atlas Tellien or Tell Atlas Mountains that average 5,000 feet (1,520 meters) high are immediately south of the coastal plains. South of the Tell Atlas is the High Plateau that averages about 3,000 feet (900 meters) above sea level. The Atlas Saharien or Saharan Atlas, the last land barrier between the Mediterranean Sea and the Sahara Desert in Algeria, rim the southern edge of the High Plateau. It has peaks as high as 7,635 feet (2,328 meters) that gradually blend southward into the Sahara.

The eastern extension of the Atlas Mountains into northern Tunisia rises from about 2,000 feet to more than 5,000 feet (600 to over 1,500 meters). The highest point is near the Algeria-Tunisia border where Mount Shanabi reaches 5,064 feet (1,544 meters).

This mountainous region of Tunisia, interspersed with fertile valleys, comprises about one-third of the country. The mountains give way to plateau averaging about 2,000 feet (600 meters) in the central part of the country. Farther south, this plateau gradually descends to numerous *shatts* or *chotts* (salty lake depressions).

Major Water Bodies. The Mediterranean Sea and the Atlantic Ocean have a major influence on the weather of the region. In the High Plateau of the Mediterranean/Atlas Zone several basins collect water during the rainy periods. These large shallow lakes dry during summer, becoming large salt flats called *chotts* or *shatts*.

Rivers and Drainage Systems. The mountains in the Mediterranean/Atlas Zone block the flow of moisture-laden winds from the Mediterranean and the Atlantic. As a result, northern and western slopes receive most of the precipitation in the region and southern and eastern slopes receive far less. For example, much more rain falls in the Tell Atlas than the Saharan Atlas. Both ranges have numerous intermittent streams known as *wadis* (from the French *oueds* - channels or water courses that are dry except during rain). None of the rivers in the Mediterranean/Atlas Zone are navigable, but some are used for irrigation and electric power generation.

The main rivers of the region are the Moulouya and Sebou in Morocco, the Chelif and Soummam in Algeria, and the Majardah in Tunisia. Many smaller rivers, some torrential, also drain the rugged terrain. On the southern and eastern side of the mountains these streams often have carved deep channels where the water flows toward the desert. Once in the desert, the streams disappear as subterranean streams or into wadis. All rivers in the region flow into the Atlantic Ocean, the Mediterranean Sea, or the Sahara Desert.

Those that flow into the Atlantic include the Sebou, the strongest river in Morocco. The Sebou flows about 450 kilometers north and then west from the Atlas Mountains to the Atlantic Ocean. Rivers flowing into the Mediterranean include the Moulouya, Chelif, Soummam, and Majardah. The Moulouya River flows north-northeast and empties into the Mediterranean about 512 kilometers from its origin in the Atlas Mountains. The Chelif, the longest and most important river in Algeria, flows

about 725 km from its origin in the Saharan Atlas. It flows north, crosses the High Plateau where it almost dries up, and then it flows westward to the sea from the Tell Atlas Mountains where it receives more water. The Soummam rises in the Tell Atlas and flows northeast about 203 km to the sea. The Majardah River and its tributaries form the principal drainage system in northern Tunisia. The only year-round river in Tunisia, it flows about 460 kilometers northeastward into the Gulf of Tunis on the Mediterranean Sea.

Vegetation. The Atlas mountains are sparsely vegetated. The Tell Atlas Mountains receive enough rainfall to have some forested sections, but even here only about one-fifth of the total area consists of forests. These grow mostly on the northern slopes. Centuries of deforestation reduced the once numerous forests to their present status. In Algeria, oak, pine, cedar, and juniper trees grow in the forested areas. In Morocco, more extensive areas of forest remain. They include cork oak, evergreen oak, juniper, cedar, fir, and pine. Northwest Tunisia has cork oak, pine, and juniper forests on the wetter mountain slopes.

The High Plateau and the plateau of Tunisia are mostly barren, but have some areas of vegetation typical of the steppes. Esparto grasses and brushwood or other types of drought-resistant shrubs grow there.

The Saharan Atlas Mountains are much more subject to desert influences, and are covered primarily with scrub bushes with only scattered stands of oak and juniper trees.

The coastal plains, which have the most fertile soil, support farming. In Morocco, the Atlantic coastal plain contains most of the arable land that supports cereal, citrus, tobacco, and grape crops. The hills and valleys of the Tell Atlas Mountains support the productive farming of cereals, grapes, figs, vegetables, oranges, and olives.

Ocean Currents/Sea-Surface Conditions. Figures 2-1 and 2-2 (see pages 2-2 and 2-3) show the major ocean currents that affect the region and the mean sea-surface temperatures. The Mediterranean current and the Canary current both affect the sea-surface temperature near the coasts and influence the weather in the Mediterranean/ Atlas Zone.

The weak Mediterranean current is due to flow from the Atlantic Ocean into the Mediterranean to replace water lost to evaporation. The Mediterranean loses water by evaporation that is three times the amount gained from rainfall and runoff. The Mediterranean current averages about 0.7 knots, but is strongest from January through March when it can reach 3 knots due to the prevailing winter westerlies and eastward moving depressions in the Mediterranean. During winter, the Mediterranean Sea is warmer than air in the boundary layer above it. This situation causes instability along the Mediterranean coast and the net transport of moisture from the sea surface into the boundary layer. Both are major causes of the increased precipitation during winter. In summer, the water temperature is cooler than the air in the boundary layer, resulting in stable conditions along the coast. Very little precipitation occurs and morning fog along the coast is more prevelant. A little more than 0.5 meters differentiates high from low tides along this coast.

The Canary Current, along the Atlantic coast, is a cold current that averages about 0.5 knots. The water is cold relative to the air mass over it, stabilizing the boundary layer and producing fog and stratus within about 30 kilometers of the coast, especially during summer. Upwelling of cold water near 30° N makes that area along the coast especially prone to fog and stratus and moderates summer tempartures more than in other coastal areas.

Azores High. Shown in Figures 2-3a - 2-3d, the Azores High is weaker in winter than in summer, allowing frontal systems associated with mid-latitude lows to pass through the area. In summer, the stronger Azores High prevents frontal passages.

SPECIAL CLIMATIC FEATURES OF THE MEDITERRANEAN/ATLAS ZONE

Atlantic Lows. Only about 9 percent of the lows affecting the region come from the Atlantic through the Strait of Gibralter. They affect the weather in northwest Morocco and along the Mediterranean coast, especially in the western Mediterranean. Only about four Atlantic Lows makes it through the Strait of Gibralter into the western Mediterranean during the year—two in winter, one in spring, and one in fall.

Atlas Lows. These lows form south of the Atlas Mountains in northeastern Algeria and can remain in the area for a couple of days before moving northward or northeastward into the Mediterranean Sea. About 14 of these occur during the year—two in winter, eight in spring, two in summer (usually June), and two in the fall (usually October). About 17 percent of the lows affecting the weather in the Mediterranean/Atlas Zone are Atlas Lows. Strong southerly or southeasterly winds associated with these lows can produce dust storms that carry dust far enough aloft that it travels over the Atlas Mountains and over the Mediterranean Zone. These strong winds also can produce siroccos that affect the Mediterranean coast.

Genoa Lows. About 74 percent of the lows affecting the region develop over the Mediterranean (especially in the Gulf of Genoa). However, not all of these depressions directly affect the region—only about 17 of 52 Genoa Lows per year directly affect the region. Seven of those occur in the winter, five occur in the spring, and five occur in the fall.

Jet-Effect Winds. Strong outbreaks from the north and south cause funneling of winds through mountain passes. Polar outbreaks cause winds from the north starting in the fall and lasting through spring. These winds can reach 40 knots or more.

Land/Sea Breezes. The Mediterranean coast experiences sea breezes from spring through fall, but they are strongest during the summer when the general circulation pattern is weakest. The weak circulation pattern allows local circulation patterns to prevail. The summer sea breeze starts at about 1000 LST and lasts until about 1900 LST. In fall and spring it doesn't start until afternoon and lasts until about 1900 LST. Along the Atlantic coast the land/sea breeze circulation is less pronounced.

Mountain/Valley and Slope Winds. These local winds occur, like land/sea breezes, during periods of weak general circulation.

Sirocco. This hot, dry wind originates in the Sahara Desert of Northwest Africa. Atlas Lows with strong southerly or southeasterly winds can cause the sirocco along the Mediterranean coast. Mediterranean depressions can also trigger the sirocco by increasing the pressure gradient from the desert to the coast as they move through the Mediterranean Sea. In Morocco and Algeria, the sirocco has the local name of *chili.* In Tunisia, it's called the *chebili.* At the coast, the sirocco's temperature and humidity are about the same as in the desert where it started, but it can carry dust to the coast with it. During the summer, temperatures of 45° C or greater are possible at the coast in a sirocco and the blowing dust can damage local vegetation. From Tangier to Tunis about 4-5 siroccos per month are average, but the spring months of April and May have the most, coinciding with the period of maximum Atlas Low occurrence.

General Weather. This region experiences a Mediterranean climate, characterized by mild, wet winters (though rainfall amounts decrease rapidly southward/southeastward from the coast). Winter begins suddenly as the eastward extension of the Azores high collapses and the mid-latitude westerlies take control of the weather. This normally happens by the beginning of November with the first invasion of cold fronts into the region. Continued high precipitation throughout the winter is partly due to the relatively high sea-surface temperatures in the Mediterranean Sea. The sea-surface temperatures in January over the Mediterranean average about 2° C higher than the air temperature. As cold air travels over this warmer water convective instability results, leading to deep cumulus development and the formation of Mediterranean depressions (Genoa Lows). Most of the rain the region receives results from these Mediterranean depressions.

Most of the lows develop over the Mediterranean (especially in the Gulf of Genoa), but not all of them directly affect the region—only about 17 of 52 Genoa Lows per year directly affect the region and only seven of those occur during the winter. However, trailing cold fronts sometimes reach as far south as 30° N in Northwest Africa. The temperature contrast between air masses across these fronts during late winter may be as great as 12-16° C. Mediterranean depressions move along these fronts, frequently drawing warm, dust-laden air from the Sahara northward—known as the *sirocco.*

Cloudy and rainy conditions associated with Mediterranean depressions and cold fronts occur intermittently through winter when as much as 80 percent of the annual precipitation falls along the Mediterranean coast. Skies remain cloudy along the coast throughout the day with these systems so that inland mountains are often not visible. In Algeria, rain falls during 10-17 days of the month near the coast and 6-7 days per month in the southern part of the area. The months of November through January are usually the wettest months. A strong cold front with a polar air mass behind it can occasionally cause snow along the Mediterranean coast. Snow, or more often soft hail, occurs more frequently at elevations above 3,280 feet (1,000 meters) with these systems.

Sky Cover. It's cloudy along the Mediterranean coast, particularly in Algeria and Tunisia where midday cloud ceilings at any altitude occur more than 50 percent of the time in January (see Figure 3-2). Cloudiness decreases on the Sahara side of the Atlas Mountains and also in southern Morocco where ceilings occur only 30 percent of the time or less. Figure 3-3, the percentage frequency of ceilings less than 3,000 feet (900 meters), indicates that there is little diurnal variation in the lower ceilings during winter. While these ceilings occur 20 percent of the time or less along the coasts, the ocean-facing slopes of the mountains experience a higher percentage of ceilings below 3,000 feet (900 meters).

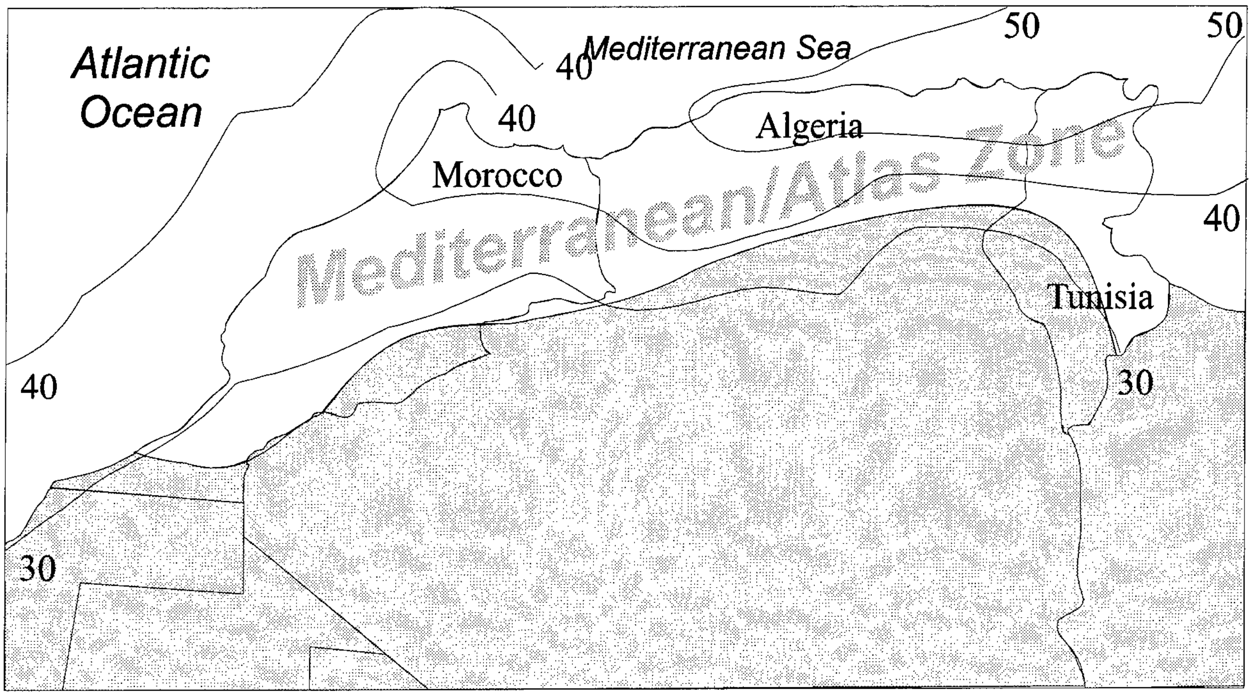


Figure 3-2. January Percent Frequencies of Ceilings. The isopleths represent the frequency of cloud ceilings at any altitude for local noon.

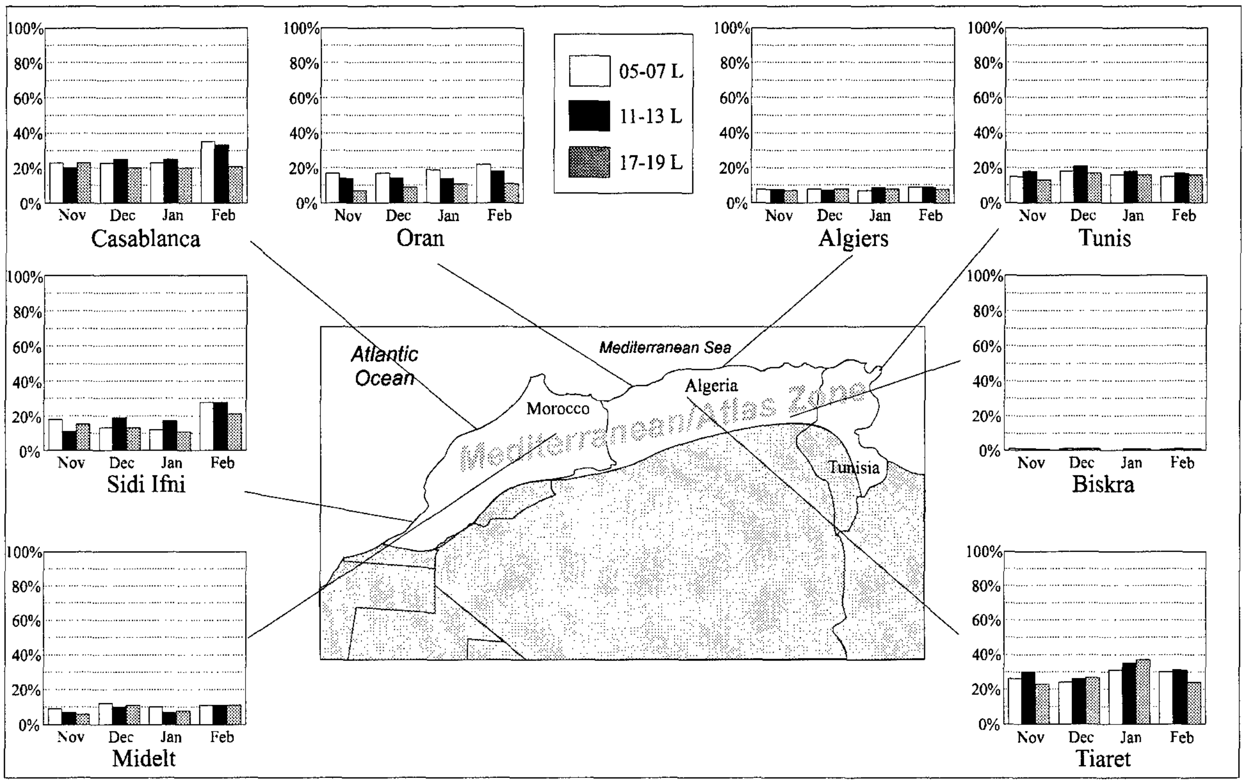


Figure 3-3. Winter Percent Frequencies of Ceilings Below 3,000 Feet (900 Meters). The graphs show a monthly breakdown of the percentage of ceilings below 3,000 feet (900 meters) based on location and diurnal influences.

Visibility. Generally good during winter, visibility less than 4,800 meters occurs less than 20 percent of the time along the Mediterranean and Atlantic coasts in the morning due to fog or mist (Figure 3-4). These areas experience fog 4-8 days per month during winter. Some locations in the Tell Atlas Mountains such as Tiaret also have fog similar to the coast. Along the Mediterranean coast, mist can also restrict visibility about 4-8 days per month in the morning. Elsewhere in the Mediterranean/Atlas Zone visibility less than 4,800 meters occurs less than 5 percent of the time. Locations in the Saharan Atlas Mountains can have blowing dust 2-4 days per month during winter. Rainfall near the coasts and snow or blowing snow in the mountains can reduce visibility to near zero.

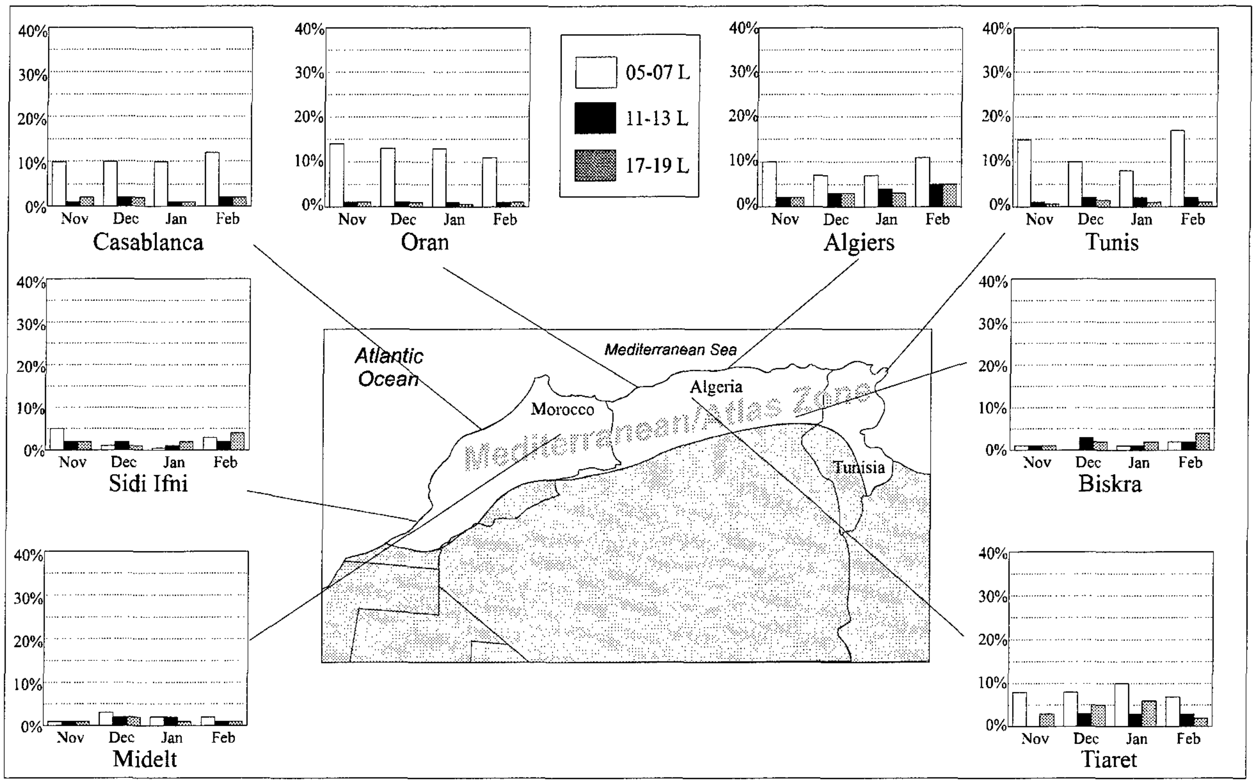


Figure 3-4. Winter Percent Frequencies of Visibilities Below 4,800 Meters. The graphs show a monthly breakdown of the percentage of visibilities below 4,800 meters based on location and diurnal influences.

Surface Winds. The most important winds are rain-bearing ones, mainly westerlies associated with eastward-moving depressions in the Mediterranean Sea, and the sirocco from the Sahara. Winds as high as 50 knots occur on the Mediterranean coast from Mediterranean Lows and along the Atlantic coast from Atlantic Lows. However, winds usually are not that strong as winds 27 knots or greater occur only 1 day per month or less along the coasts. In the mountains they are more frequent. The sirocco brings rapid weather changes as it reaches the coast with hot, dry air. The coast between Tangier and Tunis averages about 4 days per month with a sirocco. Figure 3-5 shows January mean surface winds at selected locations within the Mediterranean/Atlas Zone.

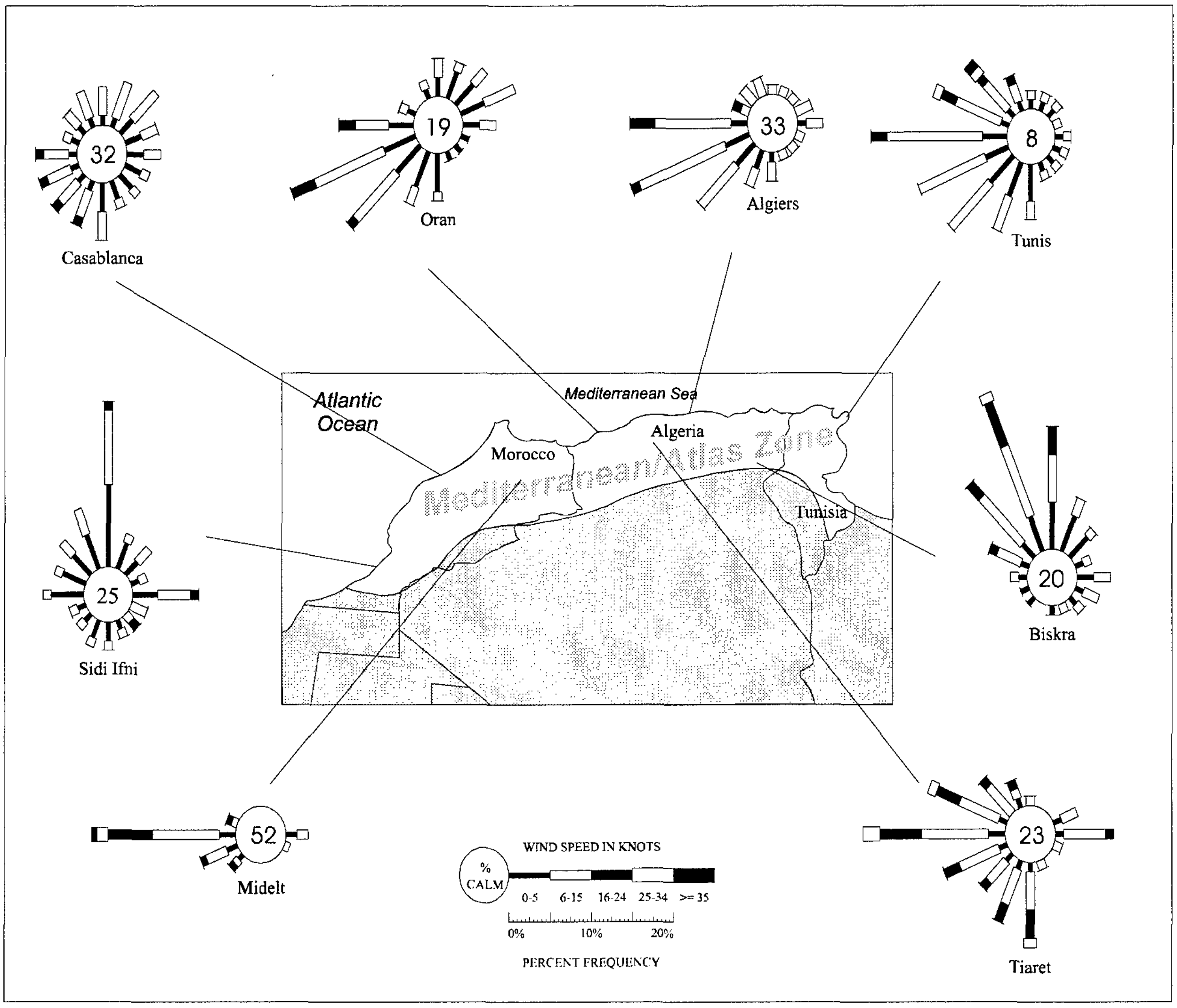


Figure 3-5. January Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Winds Aloft. Westerlies prevail throughout winter. The subtropical jet normally is south of the Mediterranean/Atlas Zone during winter. However, the polar jet with maximum wind speeds of 60 to 160 knots does occasionally reach as far south as 30° N during the winter as illustrated in Figure 2-16. When this occurs with a cold polar outbreak with strong winds behind the surface cold front, Atlas Lows form on the lee side of the Atlas Mountains and track eastward across Algeria. The January upper-air wind roses for Algiers, Algeria (Figure 3-6) shows evidence of the polar jet intrusion at the 300-mb level. The strongest winds, southwesterly at over 100 knots, agree with Figure 2-16. At Casablanca, Morocco, the upper-air winds show a similar pattern (not illustrated here), but the strongest wind, over 100 knots, is westerly. Winds over 100 knots occur about 2 percent of the time.

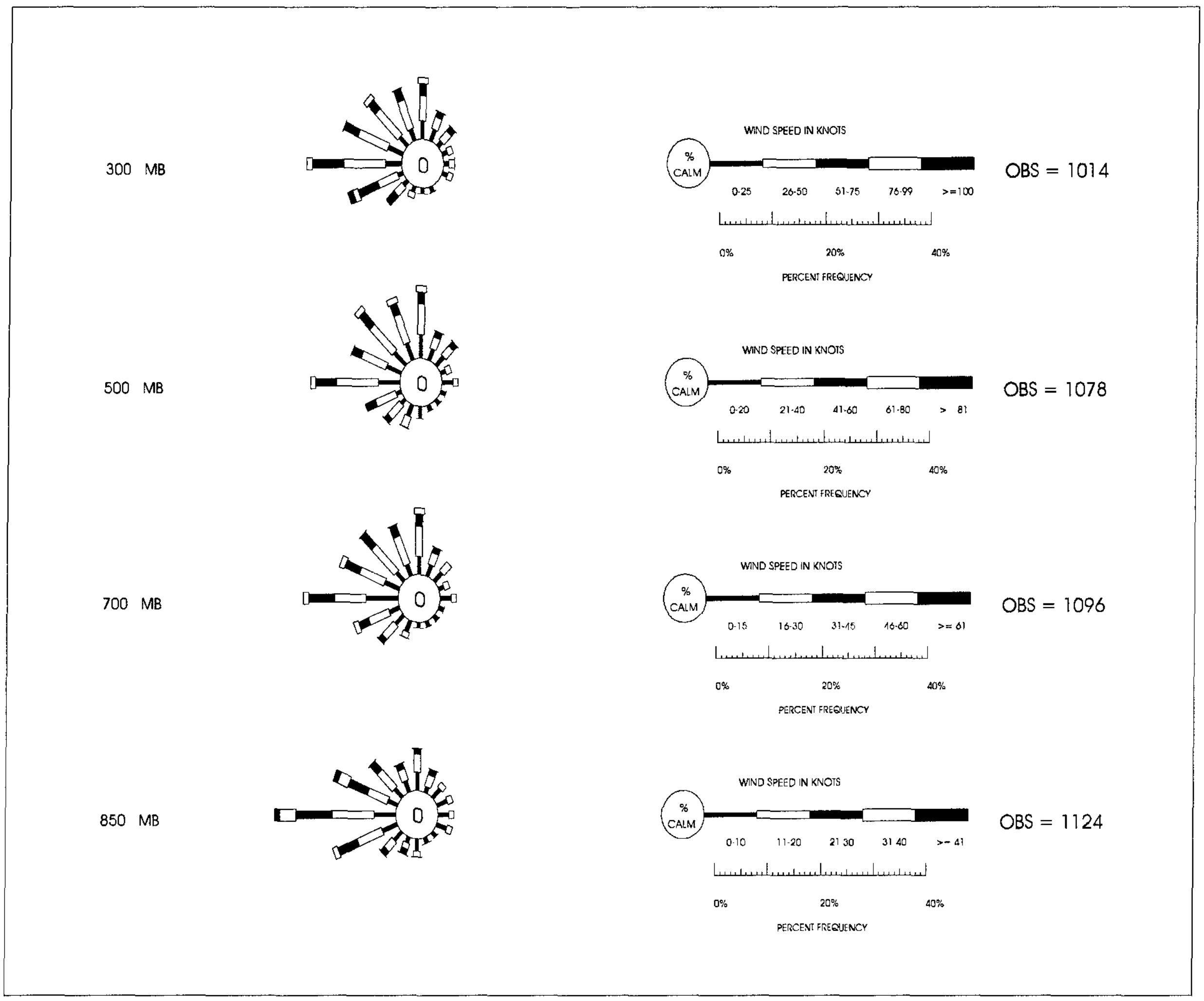


Figure 3-6. January Upper-Air Wind Roses. The wind roses depict wind speed and directions for standard pressure surfaces between 850 and 300 mb at Algiers, Algeria.

Precipitation. Winter rainfall and snowfall are caused by winter depressions, topography, and convection. Rain is common, but snow occurs in the mountains above 3,280 feet (1,000 meters) with cold polar outbreaks. Occasionally, snow occurs as low as 1,640 feet (500 meters) in the mountains and, rarely, at coastal stations. Amounts are variable across the region. The coasts and windward mountain slopes receive the most precipitation. The steppe regions or plateaus receive less precipitation than the coasts and the semi-arid regions on the lee side of the Atlas Mountains receive the least. In Algeria, for example, the annual mean precipitation decreases from 800 mm or more along the Mediterranean coast to 400-800 mm on the Mediterranean slopes of the Tell Atlas Mountains. It decreases further on the high plateau or steppes where the annual precipitation averages 200-400 mm. Finally, in the semi-arid southern part of the area bordering the Sahara, it averages only 100-200 mm. As much as 80 percent of the annual precipitation occurs during winter, mainly from November to January. Figure 3-7 illustrates the typical winter mean monthly precipitation for January. The eastern Algerian-Tunisian coastline receives more precipitation on average because Genoa Lows pass closer to that area. Likewise, northwestern Morocco receives more precipitation because of its exposure to Atlantic Lows. These two areas also have the highest number of days (10-15) with rainfall during winter (see Figure 3-8).

In Morocco, the Haut Atlas Mountains receive heavy snows in winter. Blizzards occur there and snow depths can reach 1 meter or more. Snowfall above about 1,800 meters occurs 5-10 days per month; below 1,800 meters snowfall rarely amounts to more than 1-2 cm. Some of the north and west facing slopes have snow cover for 6-9 months of the year, but the highest High Atlas peaks have snow cover the year round. Along the coast, Rabat and Casablanca have never had snow, but Tangiers has snow about 1 year out of 5 and Algiers has snow about 1 year out of 2. Snow along the coasts melts very fast. Highland stations have snow every year; elevations above about 5,900 feet (1,800 meters) in Algeria receive snowfall 5-10 days per month. The hills of northern Tunisia receive occasional snowfall, averaging only 10 days per year.

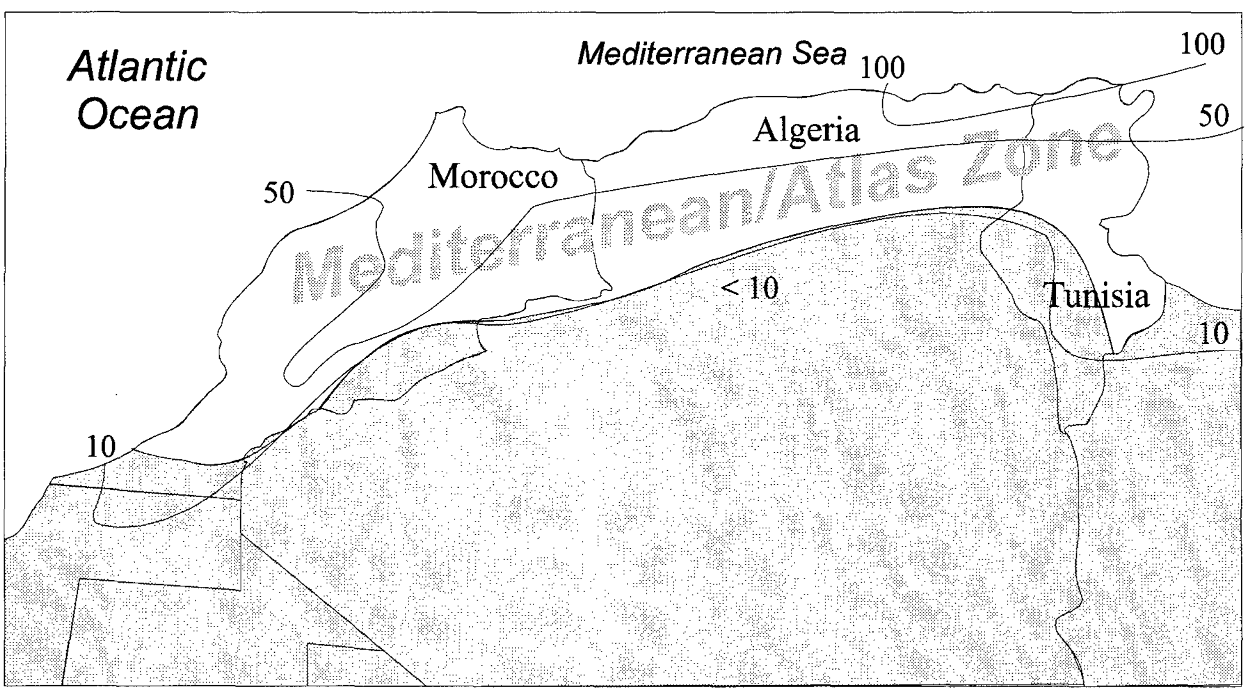


Figure 3-7. January Mean Precipitation (mm). The largest precipitation totals are along the eastern Algerian—northern Tunisian coastline.

Thunderstorms. The Mediterranean coastline and the mountains immediately inland have the most thunderstorms due to instability that develops as cool or cold airmasses move across the warm Mediterranean Sea. Showers develop in cumulus clouds and thunderstorms occur during 2-5 days per month on the Algerian coast and the slopes of the Tell Atlas Mountains. Elsewhere, thunderstorms are less numerous, occurring only one day or less per month (Figure 3-8).

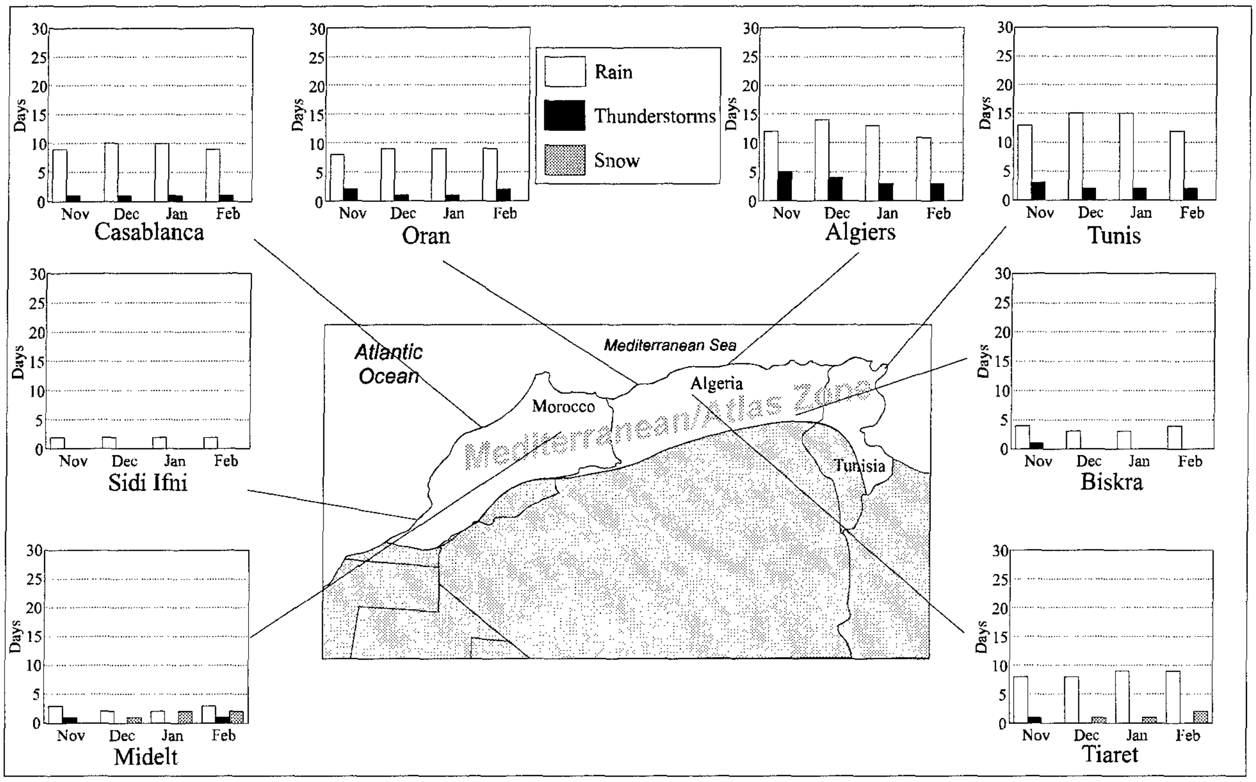


Figure 3-8. Winter Mean Precipitation and Thunderstorm Days. The graphs show the average wintertime occurrence of rain, thunderstorm, and snow days for selected cities within the Mediterranean/Atlas zone.

Temperatures. Temperatures are mild near the Mediterranean coast, with average high temperatures of 15-20° C from December through February (Figure 3-9). In the Atlas Mountains, average high temperatures are about 5° C lower, except on the desert side of the Saharan Atlas. Low temperatures near the coast are rarely below freezing, averaging 7-13° C, but in the Atlas Mountains, freezing temperatures are more common (Figure 3-10). Low temperatures there average about 5° C colder. Extreme low temperatures can go as low as -2° C near the coasts and -7° C in the mountains. Above about 5,000 feet (1,500 meters), extreme low temperatures can go as low as -20° C, or colder, with cold polar outbreaks following a cold frontal passage.

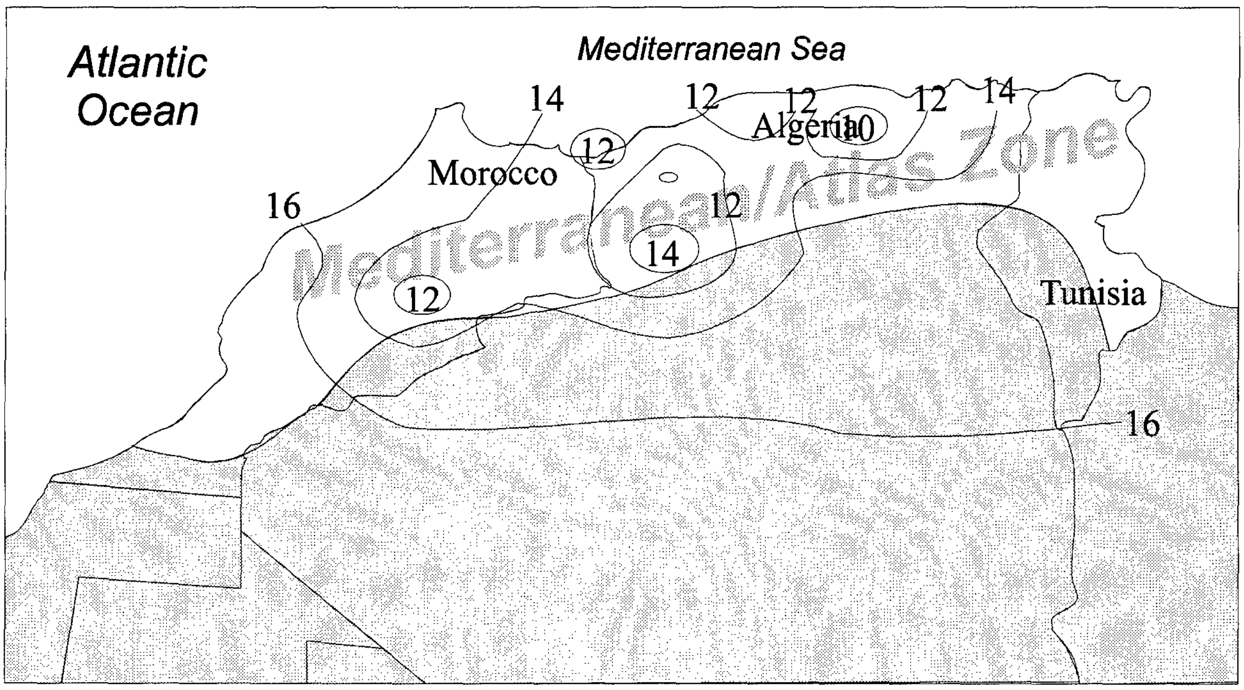


Figure 3-9. January Mean Maximum Temperatures (° C). The temperatures represent the average of all high temperatures for the coldest month during winter. Daily high temperatures will often exceed the mean. Mean maximum temperature during other winter months may also be higher, especially at the beginning and end of winter.

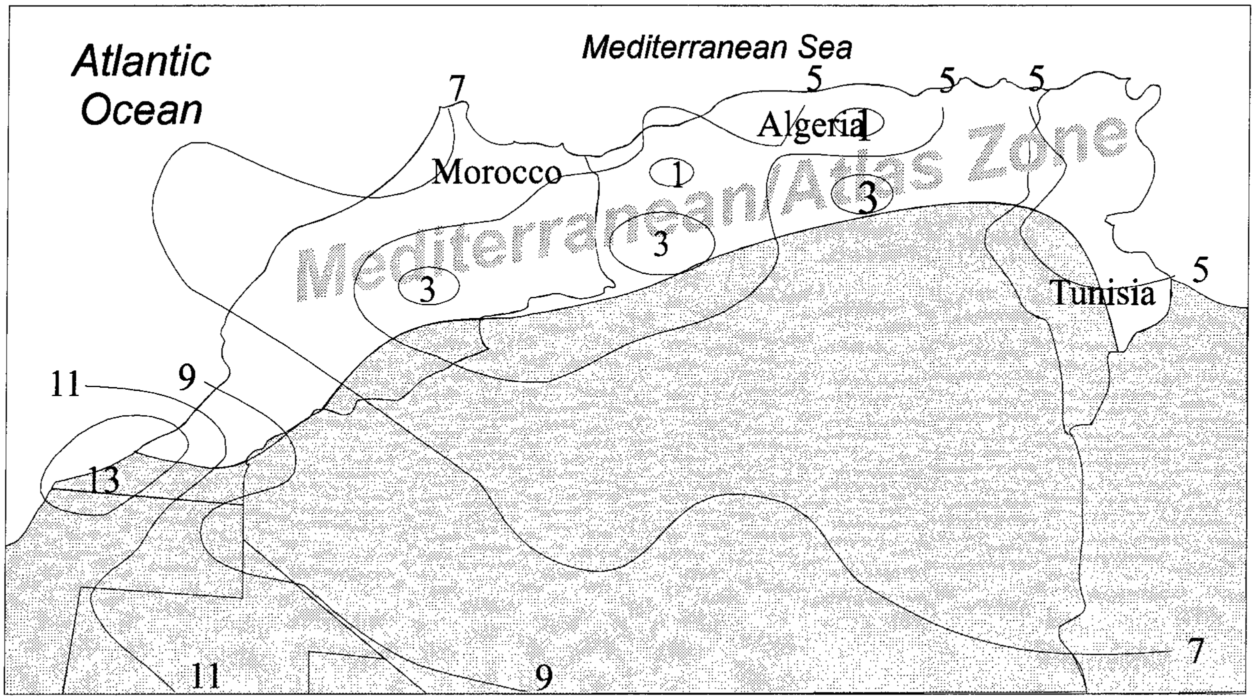


Figure 3-10. January Mean Minimum Temperatures (° C). Mean minimum temperatures represent the average of all low temperatures for the coldest month of winter. Daily low temperatures are often lower than the mean. Mean minimum temperatures at the beginning and end of winter are higher.

Hazards.

Aircraft Icing. Moderate or greater mixed icing can occur in the layered clouds above the mean winter freezing level of about 6,960 feet (2,100 meters) above sea level.

Turbulence. Turbulence in the vicinity of the mountains is common. Mountain waves that form with cold frontal passages can produce moderate to severe turbulence. The rotor cloud commonly associated with the mountain wave may not develop in the dry air on the lee side of the mountains. However, the turbulence may still be there.

Flooding. Local flooding—including flash flooding—is possible during the three wettest months of November through January. T hese floods mostly occur on the seaward sides of the mountains.

Trafficability. Topography and soil type are extremely variable in the Mediterranean Zone. Soils vary from fine-grained silt and clays to very coarse gravel, and the terrain varies from the flatlands near the coasts to steep slopes in the mountains. Consequently, the trafficability during winter varies from poor to good depending on soil type and location. The fine-grained silt and clays that predominate the flat coastal plains and lowlands become soft and muddy due to the winter rains. Vehicle movement there becomes impossible except on established roads. Coarse grained soils and small gravel provide much better trafficability. In the mountains and areas of highly dissected hills and plateaus, vehicle movement is nearly impossible the year-round due to the roughness of the surface and the steep slopes. Travel there is limited to established routes, but highways and mountain passes above 1,500 meters can be blocked by snowfall and blizzard conditions from December through February. The Atlas mountains in northern Morocco and Algeria are most likely to have snowfall—it snows there 5-10 days per month above about 5,900 feet (1,800 meters).

General. While winter begins rather abruptly, it ends with a long, unpredictable spring from March through May. Atlas Lows develop throughout the year, but they are more frequent in spring when about eight of the estimated 14 per year occur, mainly in April and May. Only five of the estimated 14 Genoa Lows that form in spring affect the Mediterranean/Atlas Zone and only one Atlantic Low makes it through the Strait of Gibralter into the western Mediterranean. Cold fronts that cross Europe and the Mediterranean steadily decrease in frequency. Also, less cloudiness, wind, and rain are associated with these systems than those in winter. The sea-surface temperature in the Mediterranean, warm at the beginning of winter, has cooled by spring. Then, as the air masses become increasingly warmer, the air in the boundary layer becomes warmer than the water temperature, creating more stable conditions. Snow is possible with a strong cold front and polar air mass near the coast early in spring, but snow and, more often, soft hail can occur at locations above 3,280 feet (1,000 meters) through April.

Sky Cover. Cloudiness gradually decreases as frontal systems from Europe and lows in the Mediterranean become less frequent. Cloud ceilings at any altitude occur more than 40 percent of the time along the Atlantic coast of northern Morocco and the Mediterranean coast at midday during April (Figure 3-11). The rest of the Atlantic coast has ceilings 30-40 percent of the time. Ceilings less than 3,000 feet (900 meters) (Figure 3-12) are most frequent in the morning to early afternoon along the Atlantic and western Mediterranean coasts and their frequency increases through spring. For example, these occur about 25-35 percent of the time in March along the Atlantic coast in the morning. By May, the frequency has increased to 40-60 percent. Increasingly stable conditions along the coasts occur as warmer air masses arrive over the relatively cooler ocean waters. This results in more morning fog and stratus that usually lifts or dissipates by afternoon. In addition, slow moving siroccos reaching the Mediterranean coast rapidly cool and pick up moisture over the cooler water. Dense sea fog and stratus can develop near the coast in those conditions. In the mountains and along the rest of the Mediterranean coast ceilings less than 3,000 feet (900 meters) mostly occur 20 percent of the time or less. They occur less frequently as the season advances toward summer.

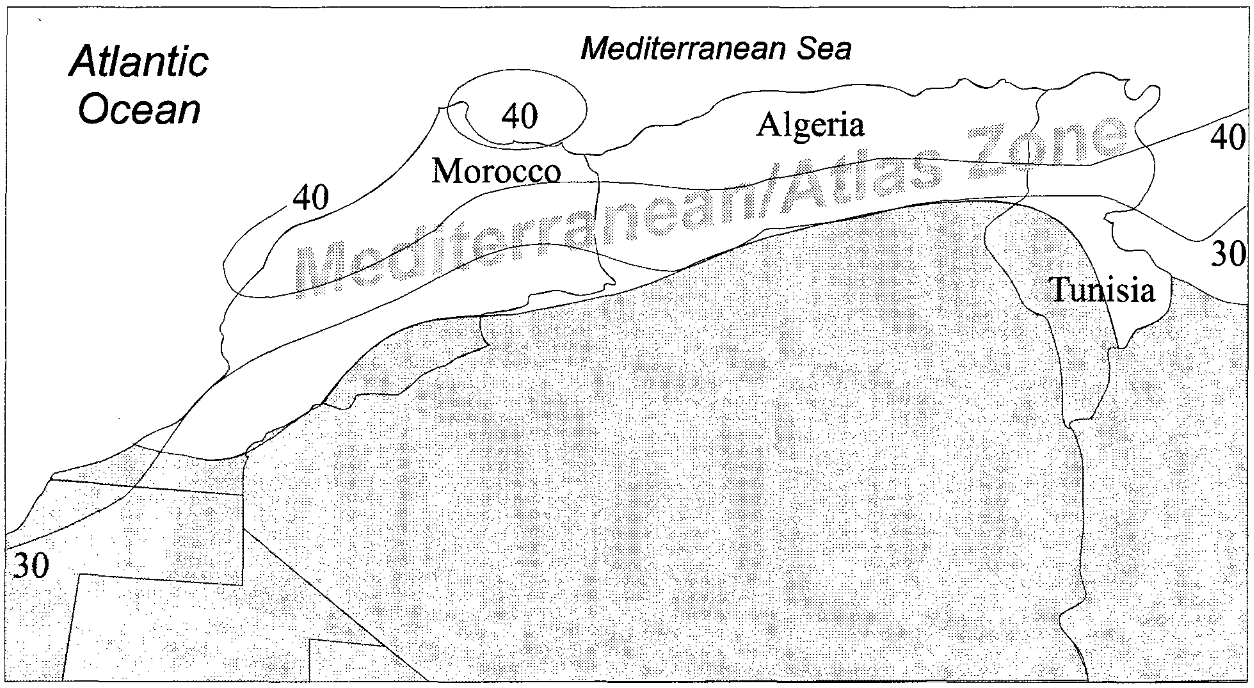


Figure 3-11. April Percent Frequencies of Ceilings. The isopleths represent the frequency of cloud ceilings at any altitude for local noon.

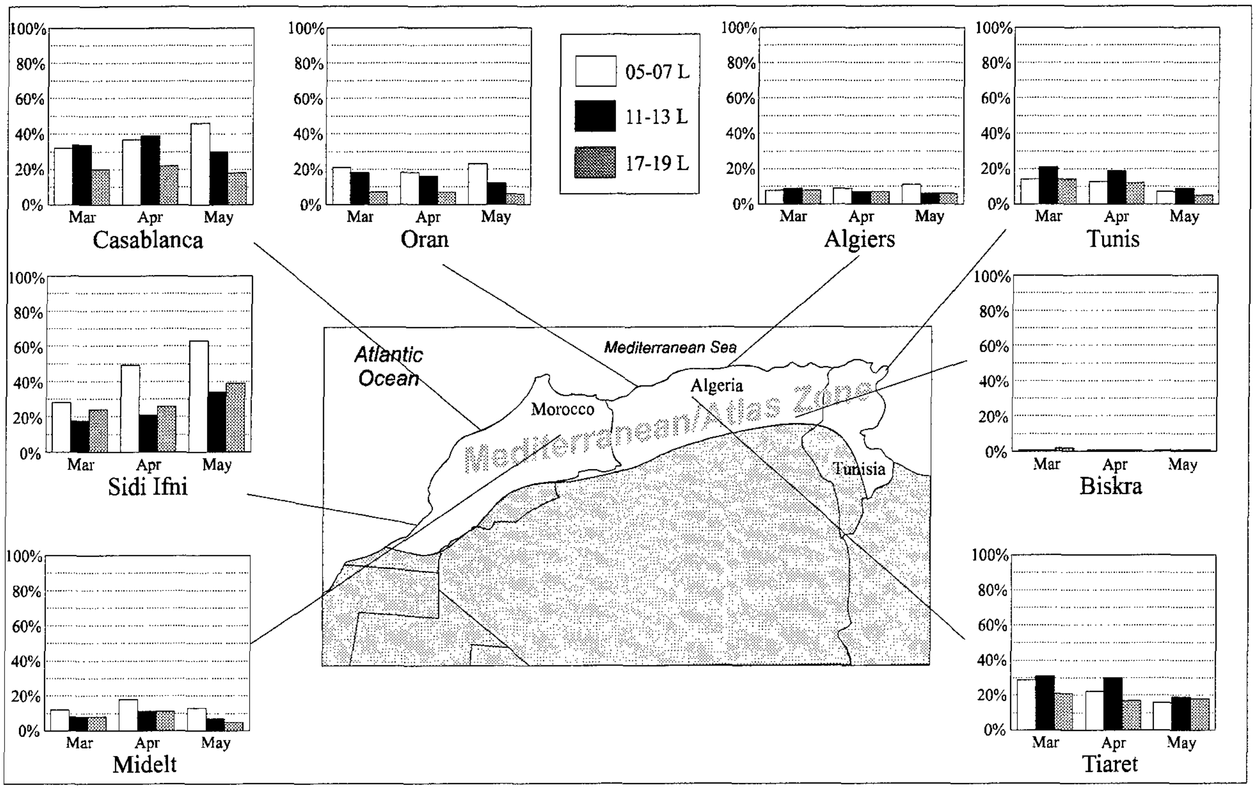


Figure 3-12. Spring Percent Frequencies of Ceilings Below 3,000 Feet (900 Meters). The graphs show a monthly breakdown of the percentage of ceilings below 3,000 feet (900 meters) based on location and diurnal influences.

Visibility. More stable atmospheric conditions help cause morning fog along the Mediterranean and Atlantic coasts. Visibilities less than 4,800 meters in the morning occur there 10-25 percent of the time (Figure 3-13). Elsewhere, the visibility is less than 4,800 meters only 10 percent or less. Along the coasts it improves by afternoon when visibilities less than 4,800 meters occur 10 percent or less.

Along the Atlantic coast fog occurs 6-8 days per month in the vicinity of Cassablanca. Along the Mediterranean coast, including locations such as Tiaret in the Tell Atlas Mountains, fog occurs 3-5 days per month. Blowing dust reduces the visibility at locations on the desert side of the Saharan Atlas Mountains. For example, Biskra has blowing dust 6-8 days per month.

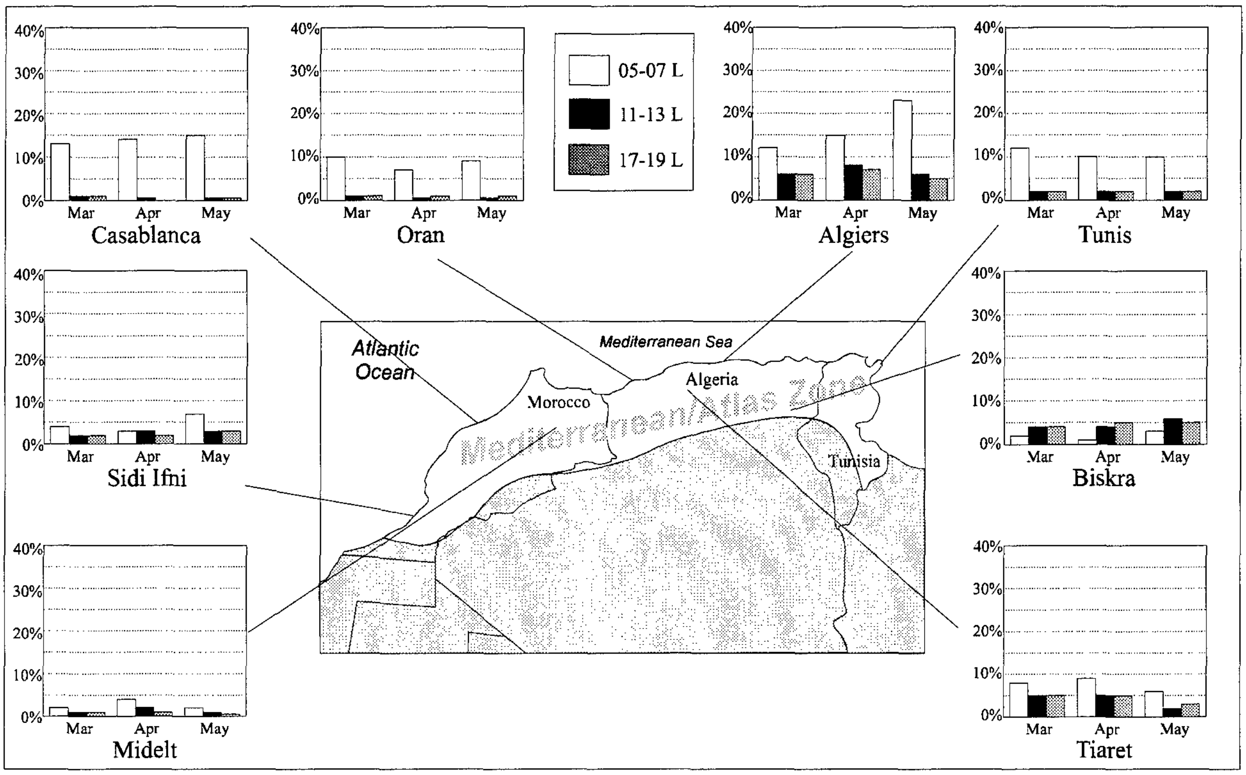


Figure 3-13. Spring Percent Frequencies of Visibilities Below 4,800 Meters. The graphs show a monthly breakdown of the percentage of visibilities below 4,800 meters based on location and diurnal influences.

SurfaceWinds. Strong winds from Mediterranean Lows occur infrequently along the coast as winds of 27 knots or greater occur on 1 day per month in April and May. The coast between Tangier and Tunis averages about 4 days per month with a sirocco. May is the month of maximum sirocco occurrence in spring. Siroccos cause a rapid change in the weather since they bring air at its hottest, driest state to the Mediterranean. The desert air where the sirocco originates is already hot and dry, but the air may dries more, and the temperature increases as the winds descend the Atlas Mountains. Sea breezes along the Mediterranean coast become more established in spring as the Azores high weakens. Early in the spring, sea breezes don't start until midafternoon and they last to early evening, but by the end of spring the sea breezes begin by late morning to early afternoon and last until about 1900L. The sea breeze averages 15-20 knots while other surface winds average 5-10 knots. Figure 3-14 shows the impact of sea breezes on local surface winds.

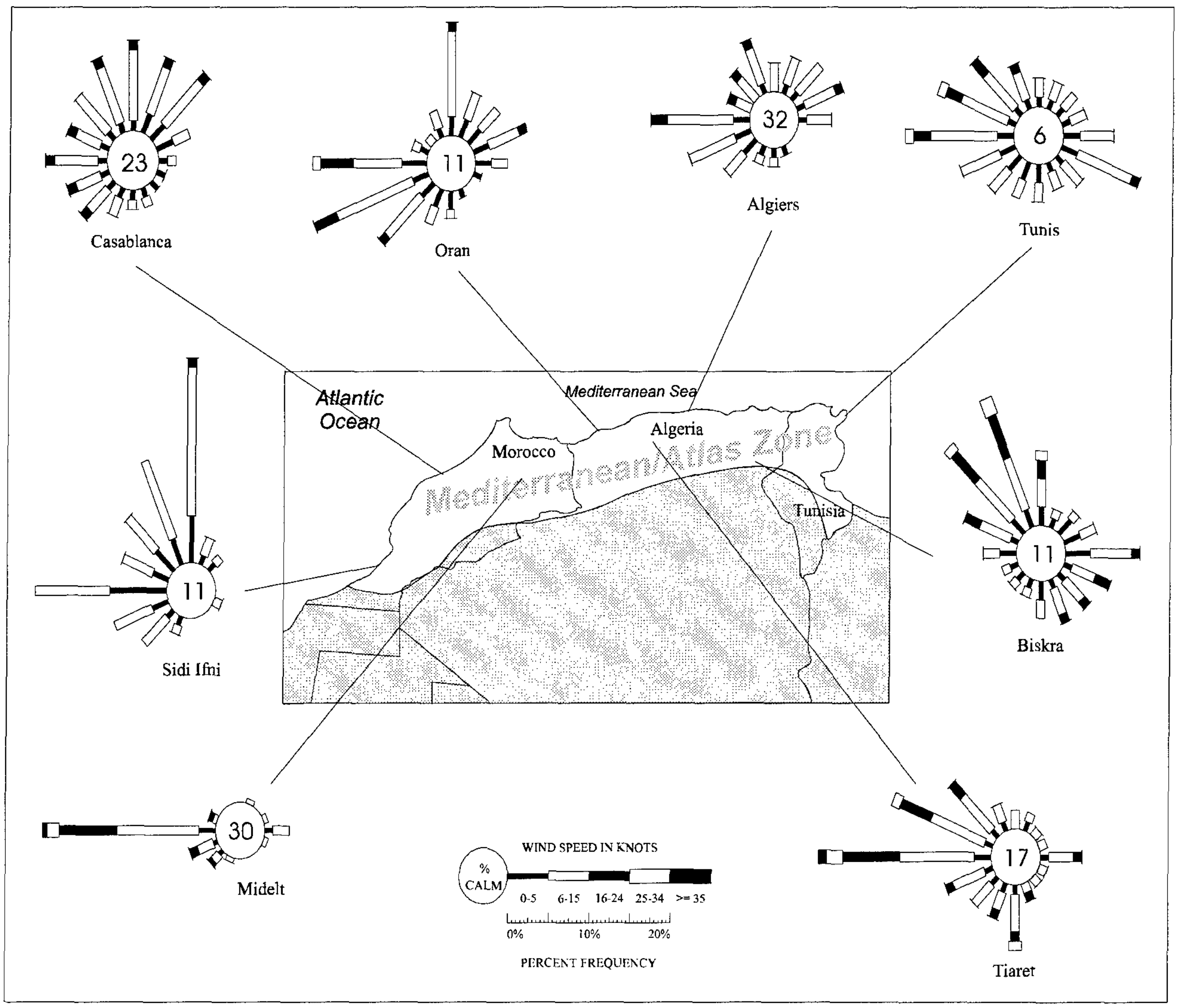


Figure 3-14. April Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Winds Aloft. Generally westerly, spring winds aloft show much less northwesterly occurrences than in winter. The polar jet might still dip as far south as 30° N in March, but it seldom migrates over the Mediterranean/Atlas Zone in April or May. The subtropical jet moves north as the Azores High increases in strength. In spring it passes over the Mediterranean/Atlas Zone as it moves from its mean winter position south of the area to its mean summer position across the northern Mediterranean (see Figure 2-7). It can have maximum speeds of 80 to 180 knots through April. Figure 3-15 indicates April winds at 300 mb over 100 knots from the southwest to west less than 5 percent of the time.

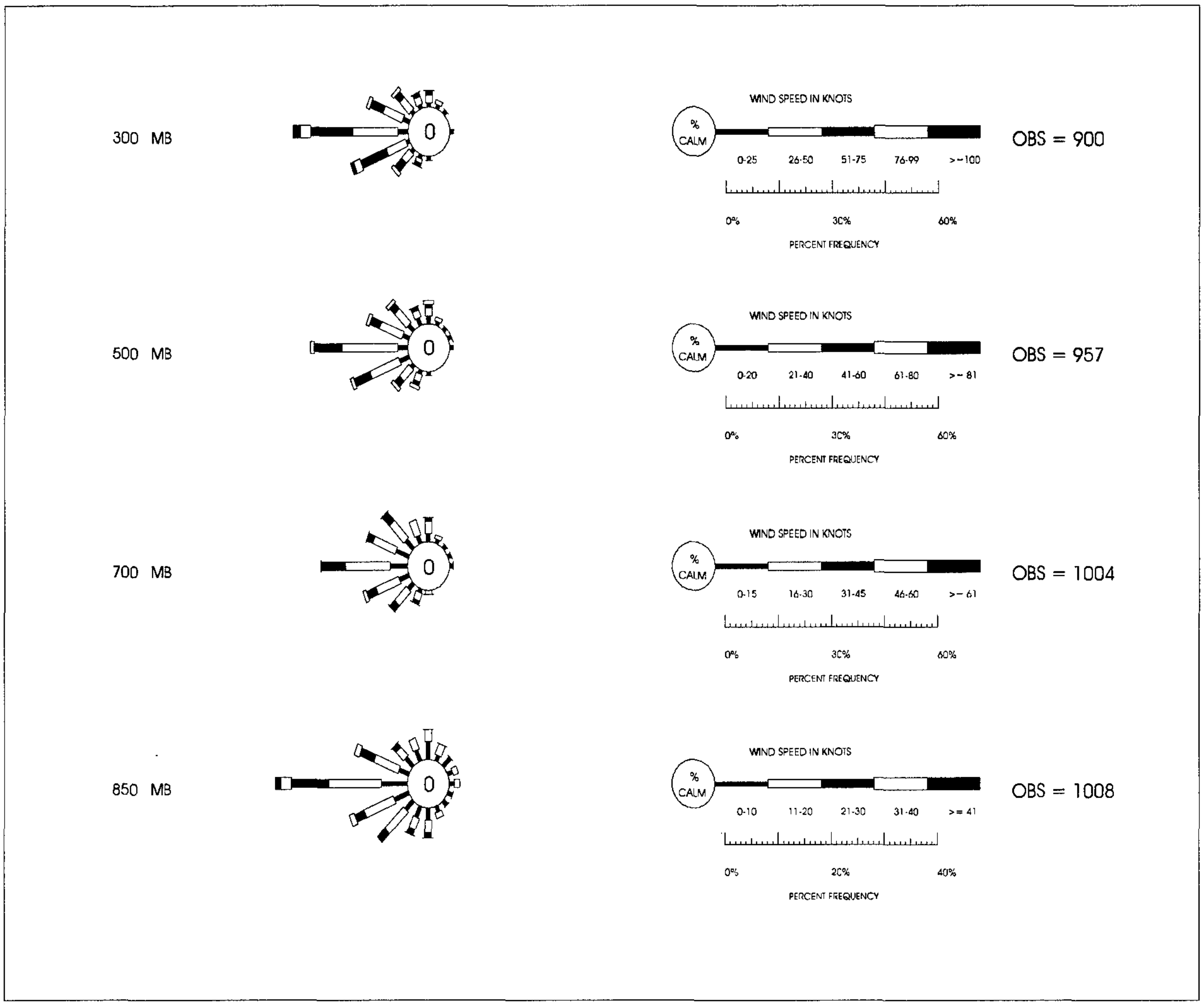


Figure 3-15. April Upper-Air Wind Roses. The wind roses depict wind speed and directions for standard pressure surfaces between 850 and 300 mb at Algiers, Algeria.

Precipitation. Precipitation decreases each month through spring. Mainly rainfall, mean amounts decrease by April to 10-50 mm except along the Mediterranean coast of Algeria where it's 50-100 mm and in northern Morocco where it's 150-200 mm (Figure 3-16). Likewise, the numbers of days with rainfall decrease each month. In March, rainfall days vary from 9 days along the northwestern Moroccan coast to nearly 15 days along the Tunisian coast. By May, the rainfall days decrease to 5-8 days as the Genoa Lows and fronts decrease in frequency (see Figure 3-17). Snowfall is still possible in the Atlas mountains of northern Morocco and Algeria at elevations above 3,280 feet (1,000 meters) during March and possibly April.

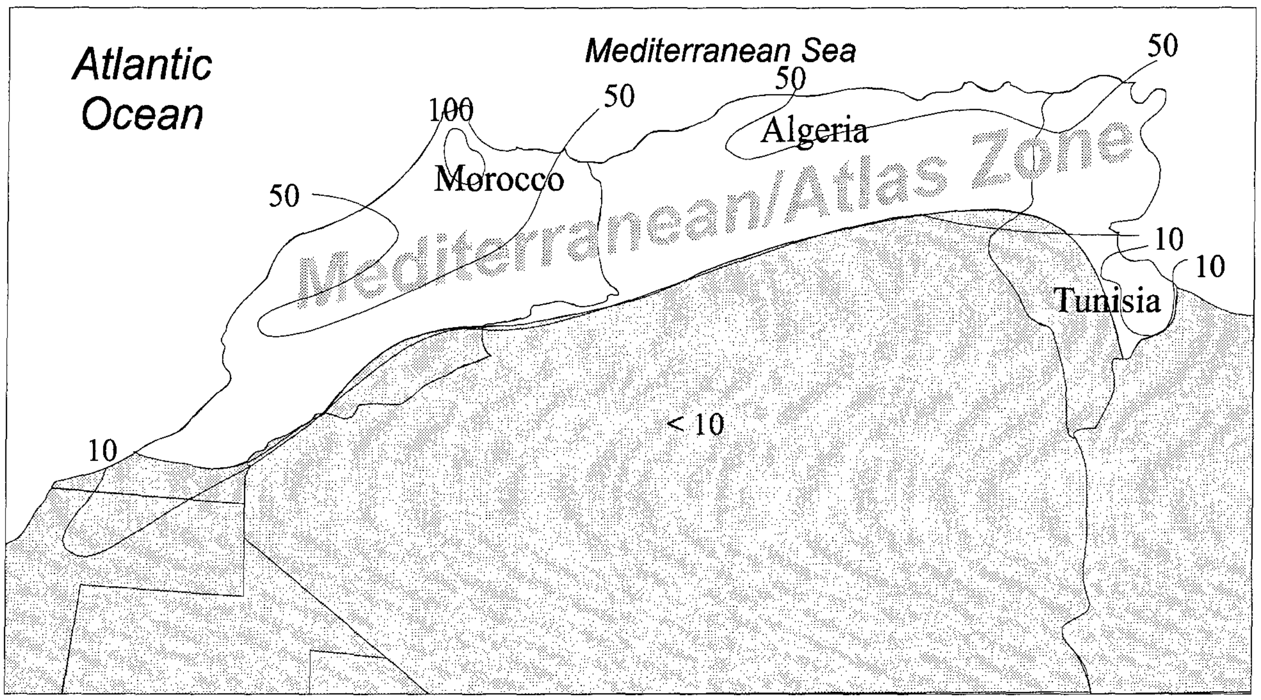


Figure 3-16. April Mean Precipitation (mm). The isopleths show that northern Morocco has the most precipitation.

Thunderstorms. Thunderstorms occur 5 days or less along the Mediterranean coast from Tunisia to western Algeria (Figure 3-17). From there westward and along the Atlantic coast they are rare. The windward slopes of the mountains experience thunderstorms about as frequently as the coasts; the lee side less frequently.

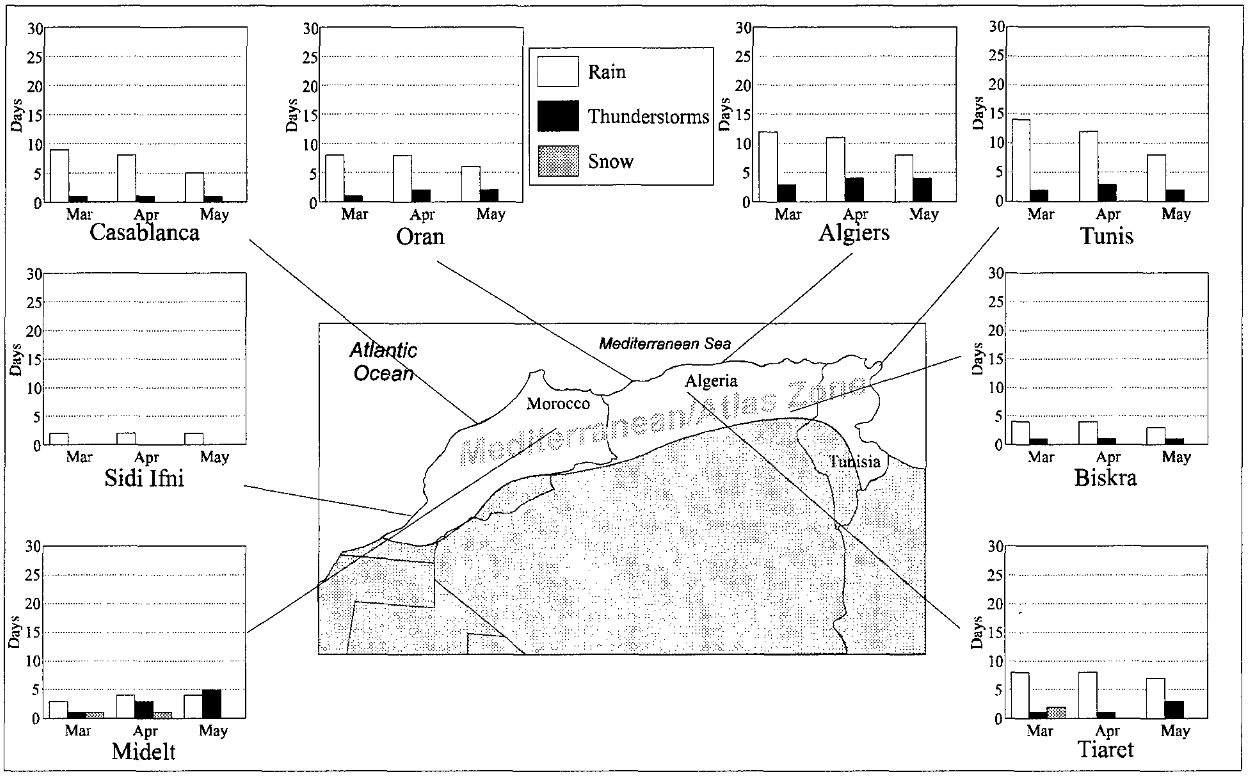


Figure 3-17. Spring Mean Precipitation and Thunderstorm Days. The graphs show the average springtime occurrence of rain, thunderstorm, and snow days for selected cities in the Mediterranean/Atlas Zone.

Temperatures. It's warm and getting hot near the Mediterranean and Atlantic coasts. Average high temperatures of 18-24° C are common there during spring (see Figure 3-18) and extreme high temperatures can reach 40° C by May as the summer weather pattern settles in. In the Atlas Mountains, average high temperatures are lower, about 13-21° C. Low temperatures near the coasts average 8-15° C (Figure 3-19); in the mountains they average 4-10° C. Extreme lows below freezing are possible in March near the coasts, but in the mountains extreme lows below freezing can occur throughout spring.

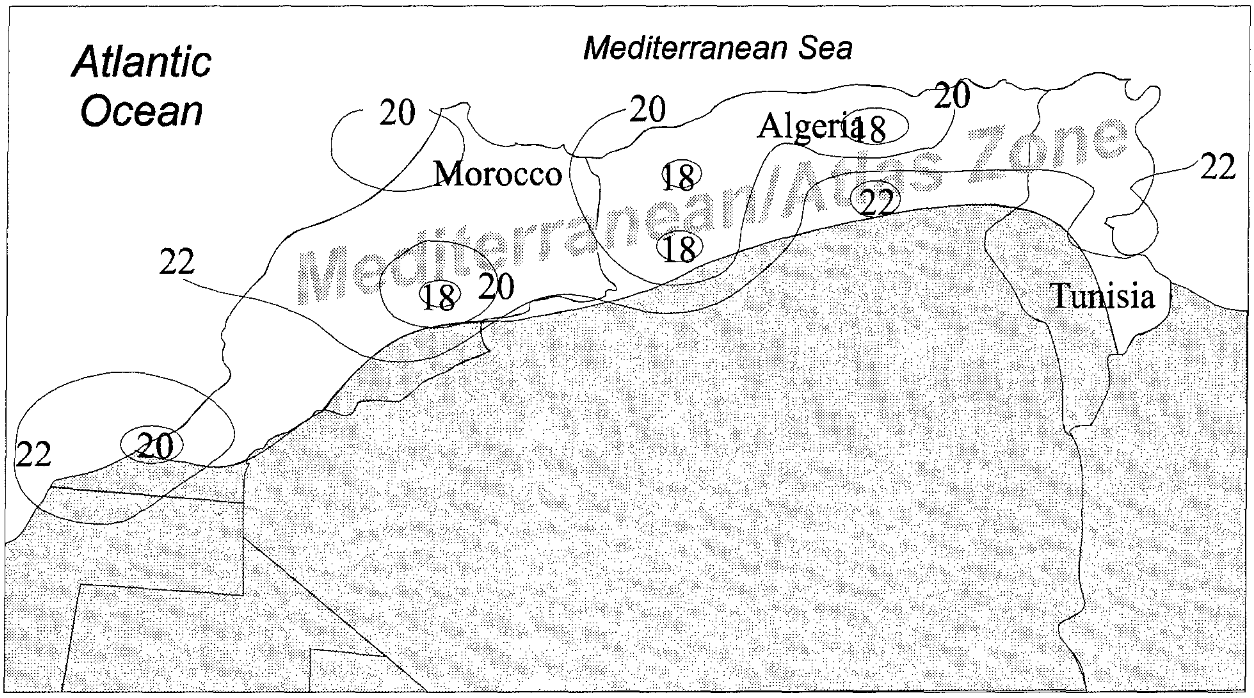


Figure 3-18. April Mean Maximum Temperatures (° C). These temperatures represent the average of all high temperatures for the most representative month of the season. Daily high temperatures often will be higher than the mean. Mean maximum temperatures during the end of spring are higher.

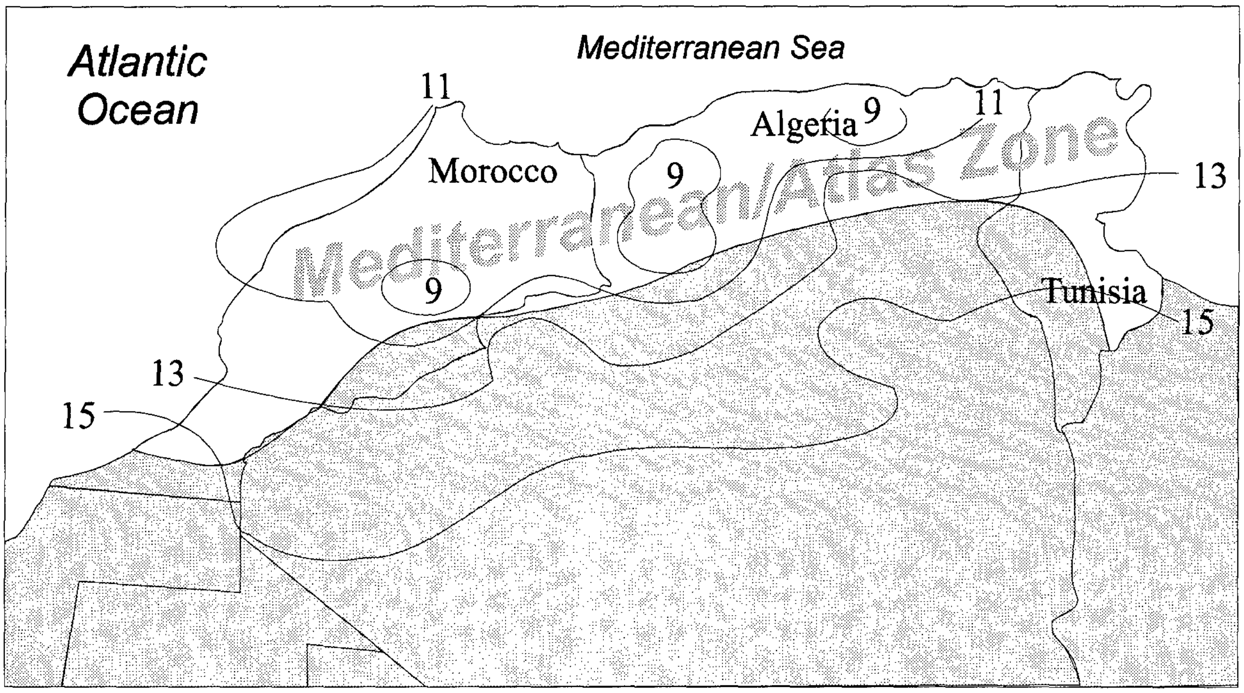


Figure 3-19. April Mean Minimum Temperatures (° C). Mean minimum temperatures represent the average of all low temperatures for the most representative month of the season. Daily low temperatures are often lower than the mean. Mean minimum temperatures at the beginning of spring are lower.

Hazards.

Aircraft Icing. Moderate or greater aircraft icing can occur in the layered clouds above the mean freezing level of about 6,900 feet (2,100 meters) above sea level early in spring.

Turbulence. Moderate or greater turbulence in the vicinity of the mountains is a hazard during frontal passages early in the season.

Trafficability. Topography and soil type are extremely variable in the Mediterranean/Atlas Zone. Soils vary from fine-grained silt and clays to very coarse gravel and the terrain varies from the flatlands near the coasts to steep slopes in the mountains. Consequently, the trafficability during spring varies from poor to good depending on soil type and location, but it usually improves each month of spring as rainfall steadily decreases. The fine-grained silt and clays that predominate the flat coastal plains and lowlands become soft and muddy due to the early spring rains. Vehicle movement there would be impossible except on established roads. Coarse grained soils and small gravel provide much better trafficability. In the mountains and areas of highly dissected hills and plateaus, vehicle movement is nearly impossible the year-round due to the roughness of the surface and the steep slopes. Travel would be limited to established routes, but at elevations above 5,000 feet (1,500 meters) snowfall is still possible through spring. Highways and mountain passes can be blocked by snow and drifting snow.

General Weather. Summer is hot, dry, and humid. By mid-June the Azores high dominates the weather pattern. Also, the sea surface is now relatively cooler than the air in the boundary layer, creating more stable conditions. Calm, sunny, hot, and humid weather with little rainfall prevails throughout the region. Daily land and sea breezes condition the daily weather near the coast, but their effect diminishes inland, making conditions there oppressive. On the desert side of the mountains, the air is dry and the temperatures higher.

Sky Cover. The Atlantic coastline of Morocco is the only area of the Mediterranean/Atlas Zone that has any significant clouds during summer (Figure 3-20). Low stratus clouds and fog there cause ceilings 30-50 percent of the time, on average. The northern Moroccan coastline and the remainder of the region are almost cloud free. The cold Canary current flowing from the north along the Atlantic coast helps create the conditions for fog and stratus similar to those along the California coast in the United States. Ceilings occur as much as 80 percent of the time in the morning in southern Morocco (Figure 3-21). Conditions improve some during the afternoon, but ceilings below 3,000 feet (900 meters) still occur as often as 40-50 percent of the time. The Atlas Mountains have ceilings less than 3,000 feet (900 meters) 10 percent or less at most locations. The Mediterranean coast experiences ceilings less than 3,000 feet (900 meters) more frequently in the morning than in the afternoon due to fog (up to 30 percent in western Algeria). By afternoon, ceilings are nearly non-existent.

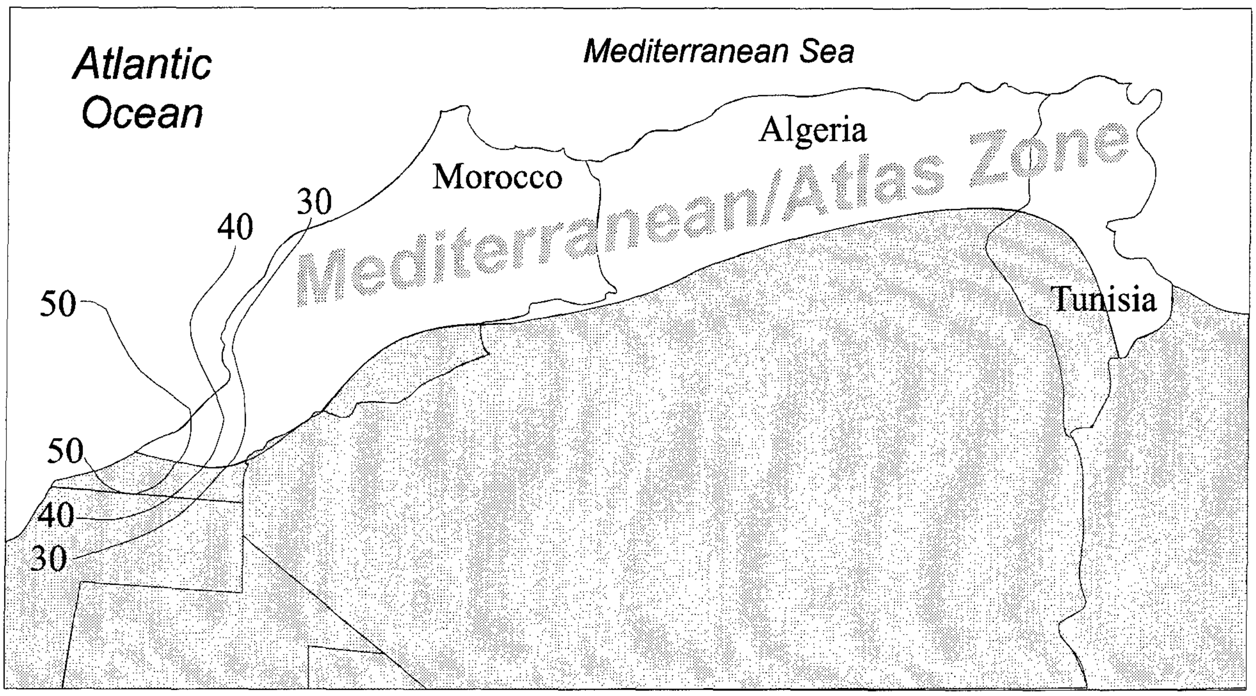


Figure 3-20. July Percent Frequencies of Ceilings at 1200L. These percentages represent the frequency of cloud ceiling at any altitude.

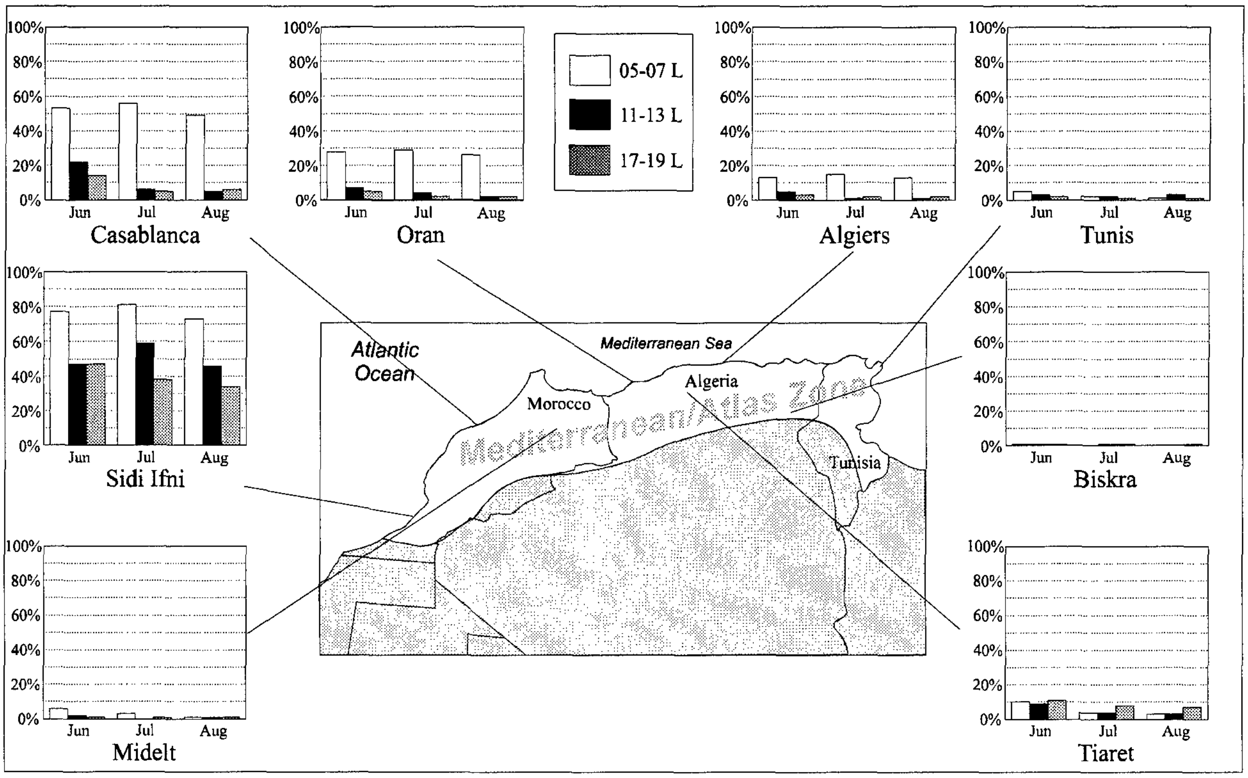


Figure 3-21. Summer Percent Frequencies of Ceilings Below 3,000 Feet (900 meters). The graphs show a monthly breakdown on the percentage of ceilings below 3,000 feet (900 meters) based on location and diurnal influence.

Visibility. The zone has good visibilities, except along the coasts in fog and stratus that occur throughout the season. The morning percentage frequency of visibility less than 4,800 meters is highest at about 20-25 percent in the vicinity of Algiers and along the Atlantic coast of Morocco during July (Figure 3-22). By afternoon, lower visibilities occur only 10 percent or less. Fog occurs about 5 days per month at Algiers and 4-8 days at Casablanca, but elsewhere it occurs less than that. Blowing dust occurs in the Saharan Atlas Mountains 5-8 days per month.

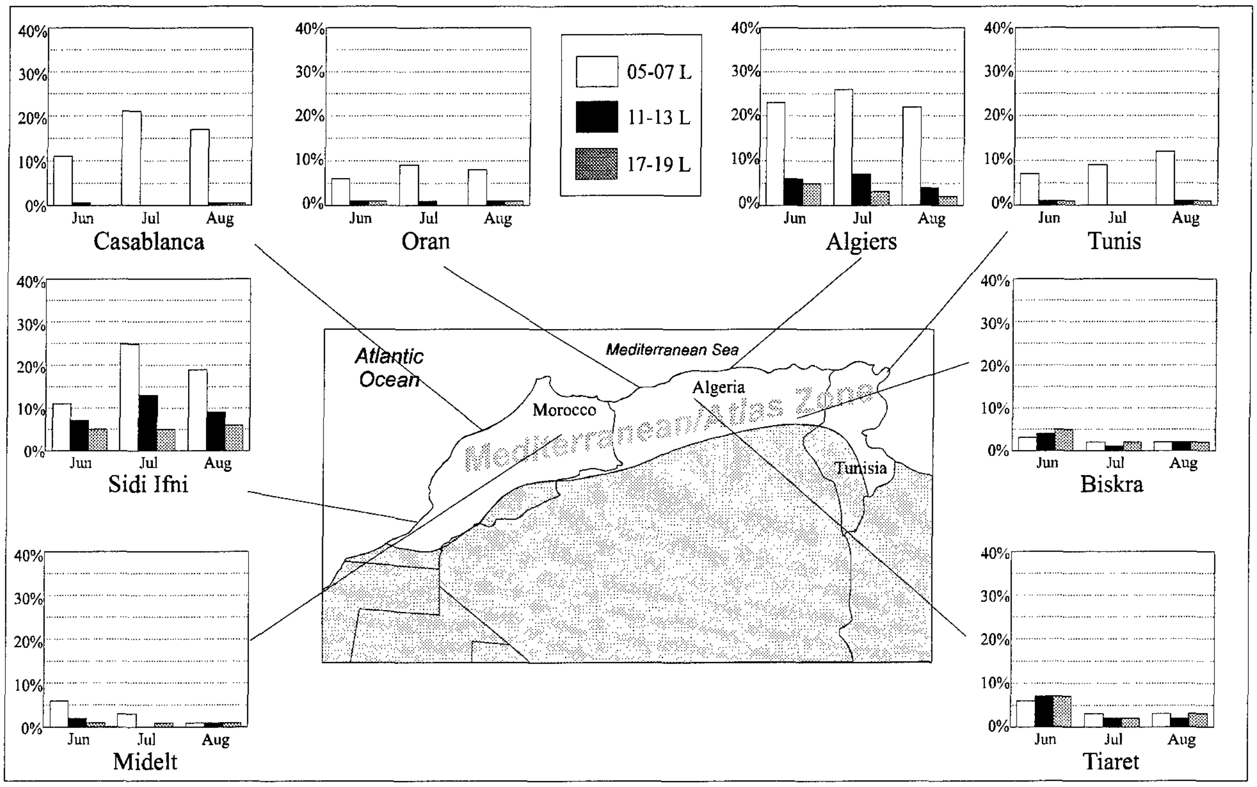


Figure 3-22. Summer Percent Frequencies of Visibilities Below 4,800 Meters. The graphs show a monthly breakdown on the percentage of visibilities below 4,800 meters based on location and diurnal influences.

Surface Winds. A weak general northeasterly circulation pattern makes local wind conditions more prominent than in other seasons. Land/sea breezes are strongest at this time of year, especially along the Mediterranean coast (see Figure 3-23). Sea breezes start by about 1000L and persist until about 1900L when winds change direction to the land breeze or become light and variable. During the afternoon, sea breezes average 15-20 knots. The wind direction from the water to the station depends upon the local terrain. The Mediterranean coast from Tangier to Tunis experiences about four siroccos or chilis per month. June has the most siroccos during the summer.

Winds Aloft. Upper-level winds are predominantly westerly with maximum speeds at 300 mb of 75 knots or less (Figure 3-24). The subtropical jet is weakest during the summer.

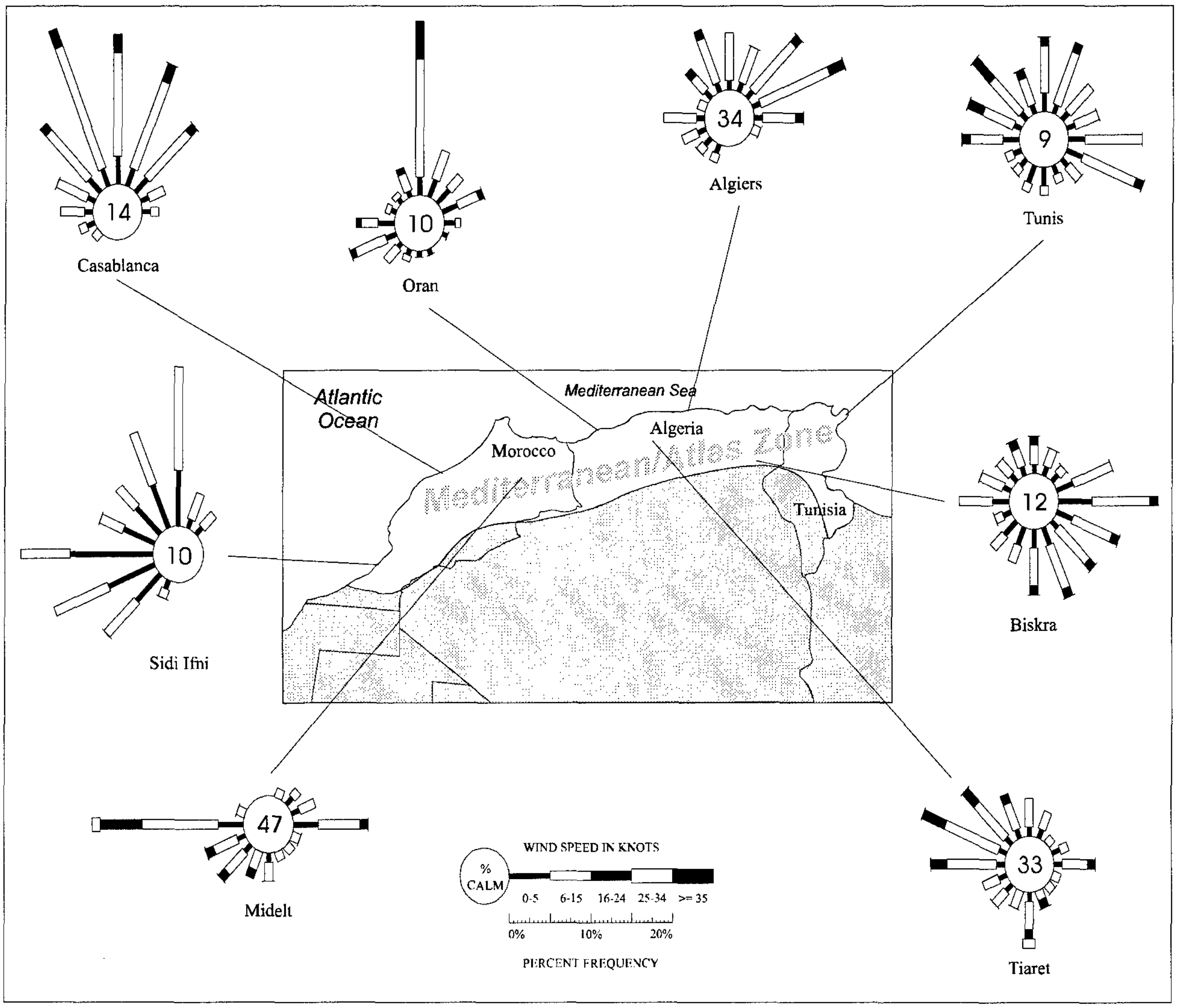


Figure 3-23. July Surface Wind Roses. The figure shows prevailing wind directions and range of speeds based on percent of frequency and location.

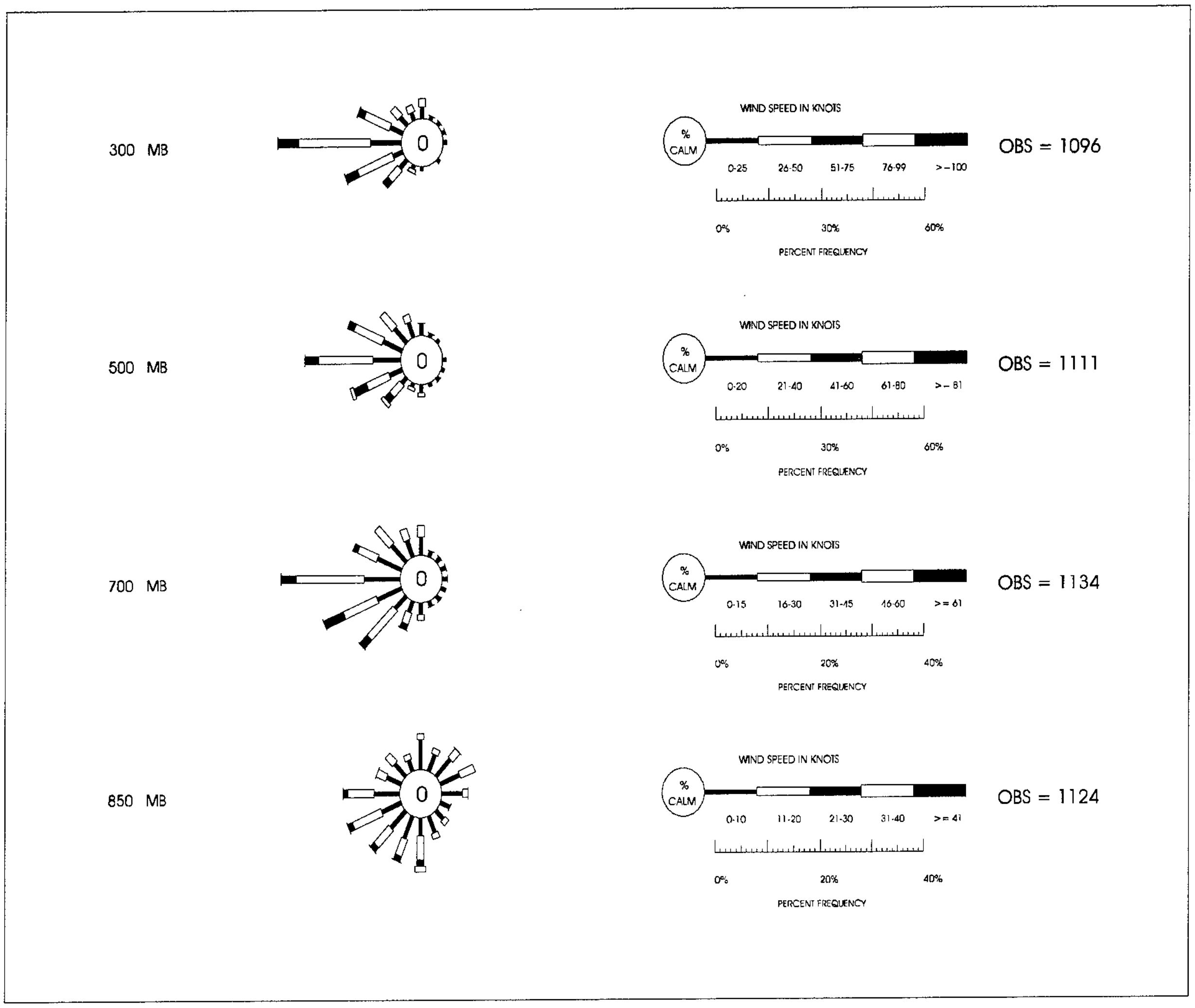


Figure 3-24. July Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard surfaces between 850 and 300 mb.

Precipitation. A few showers and thunderstorms produce the limited rainfall during the summer. Mean monthly precipitation is 10-50 mm early in summer, but decreases to less than 10 mm nearly everywhere in July and August except at some higher elevations in the mountains (Figure 3-25). It rains on about 5 days during June along the Mediterranean coast and even fewer days in July and August. Elsewhere, rain occurs less frequently (Figure 3-26). The peaks of the Haut Atlas Mountains in Morocco can receive snow in summer.

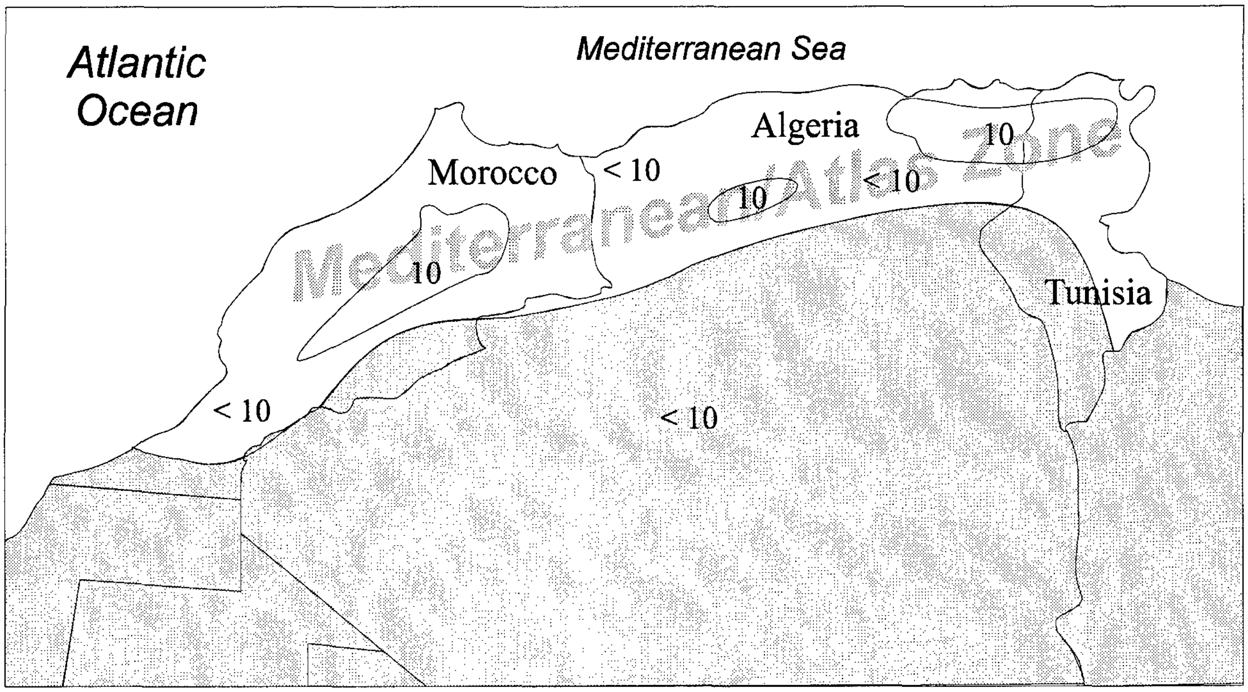


Figure 3-25. August Mean Precipitation (mm). The isopleths depict the limited amount of rainfall received during the summer season.

Thunderstorms. Only five or fewer thunderstorm days per month occur along the Mediterranean coast. Thunderstorms are rare along the Atlantic coast due to the stabilizing influence of the Canary Current. However, in the mountains and plateau of northern Morocco, thunderstorms occur as frequently as 7 days during August (Figure 3-26).

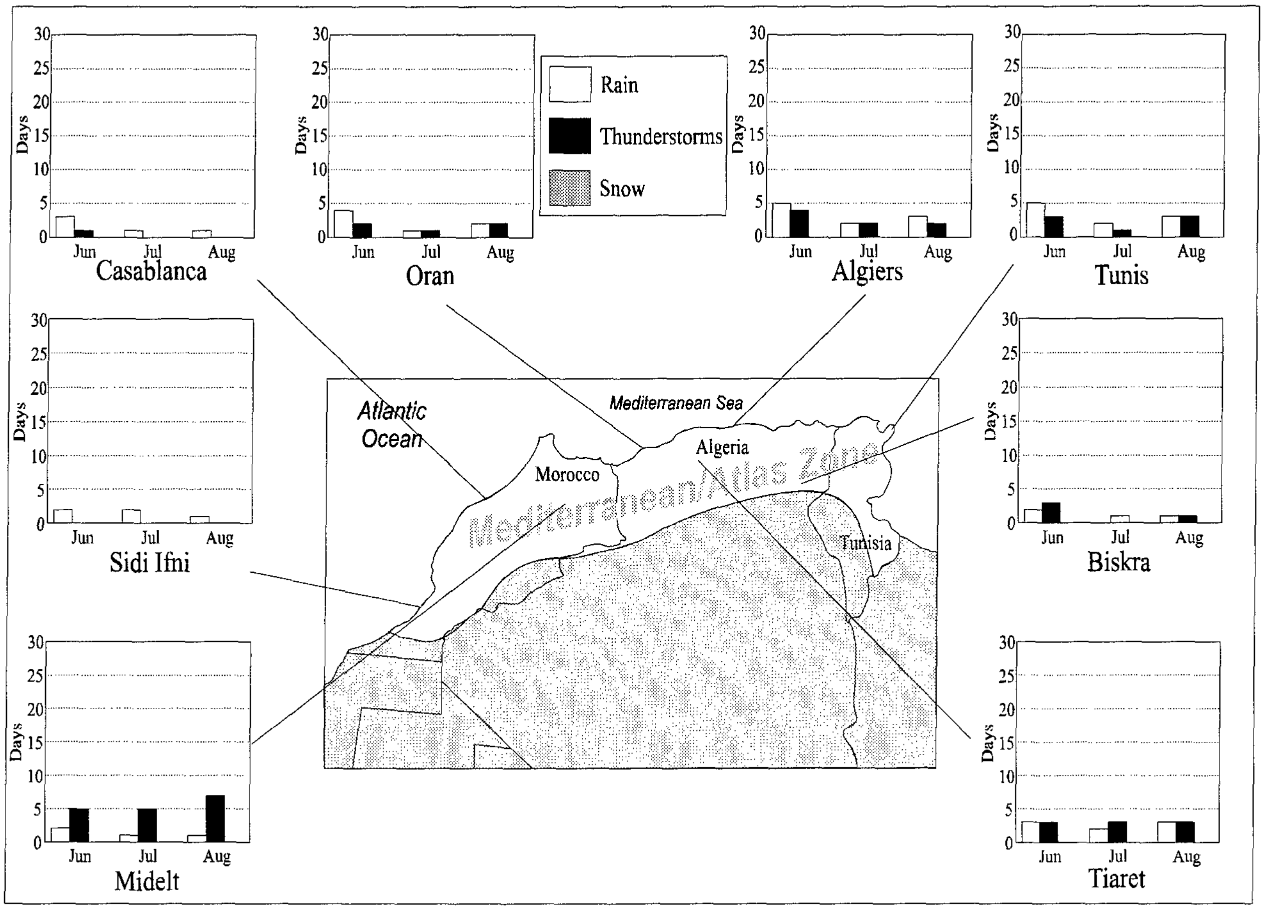


Figure 3-26. Summer Mean Precipitation and Thunderstorm Days. The graphs show the average summertime occurrence of rain and thunderstorm days for selected cities in the Mediterranean/Atlas zone.

Temperatures. Summer temperatures increase eastward and southward away from the coasts in the Mediterranean/Atlas Zone. This is due to the cooling effect of the Canaries Current along the Moroccan coast and the Mediterranean current along the northern coast. For example, during July, an average high temperature of about 23° C near the coast increases to 30° C at 3,280 feet (1,000 meters) elevation at the same latitude. Average high temperatures of 27-29° C along the coast increase on the Saharan side of the mountains to 38° C and higher (Figure 3-27). Siroccos can cause extreme high temperatures along the Mediterranean coast, as high as 45° C or more. At 1,500 meters, temperatures rarely reach as high as 38° C.

Low temperatures during summer average 18-22° C over much of the region with extreme lows reaching 10° C (Figure 3-28). The higher elevations experience low temperatures about 5° C lower with extreme low temperatures just above freezing.

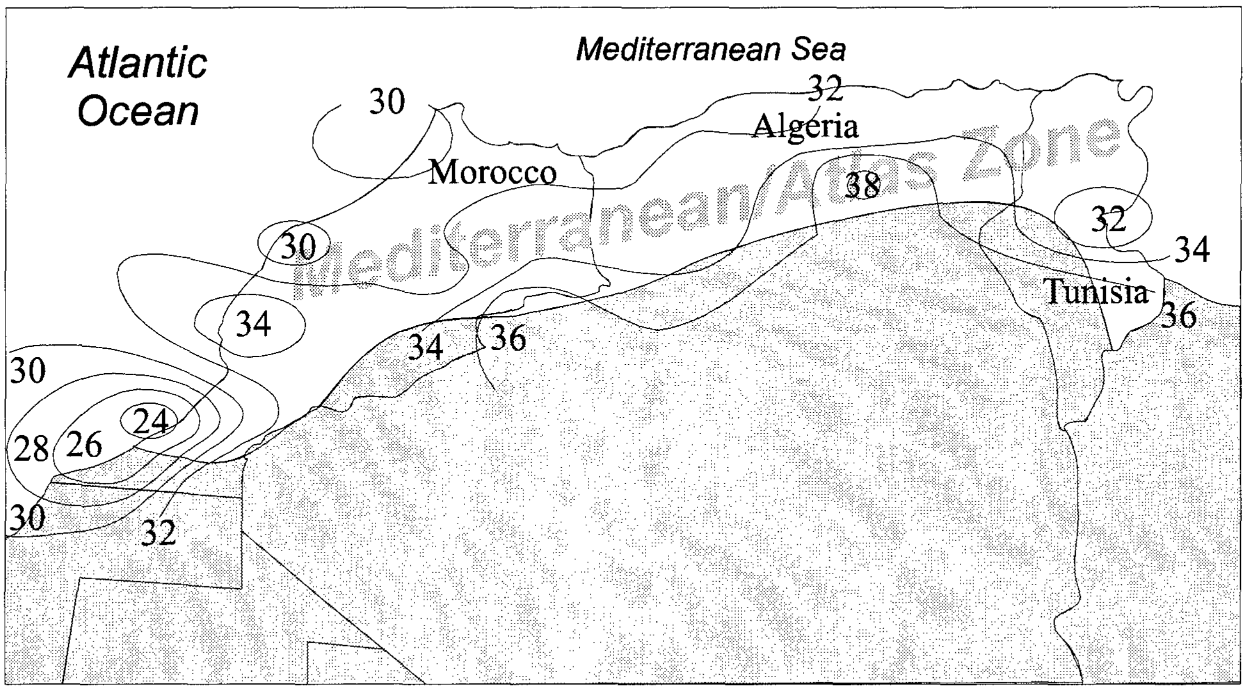


Figure 3-27. July Mean Maximum Temperatures (° C). These temperatures represent the average of all high temperatures for the most representative month of the season. Daily high temperatures will often be higher than the mean.

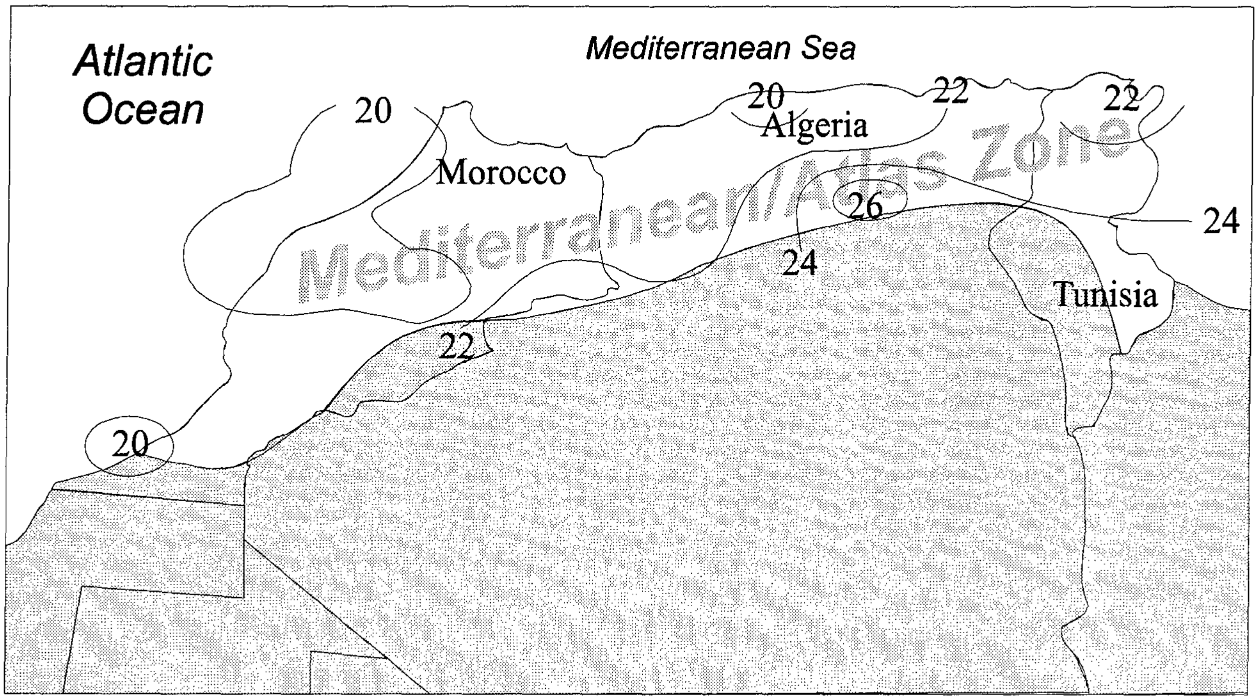


Figure 3-28. July Mean Minimum Temperatures (° C). Mean minimum temperatures represent the average of low temperatures for the most representative month of the season. Mean minimum temperatures at the beginning and ending of summer are lower.

Hazards. The sea breeze conditions the hot, humid conditions near the coasts to about 30 km inland. Without the effects of the ocean breeze, conditions inland are oppressive as indicated by the 30-31° C WBGT in July in the Mediterranean/Atlas Zone (Figure 2-29).

Trafficability. Summer is the dry season and off-road vehicle travel is limited only by steep slopes and rough surfaces and flash floods reslting from thunderstorms. Wadi/conyon bottons con rapidly become temporarily impossible to all vehicles. Otherwise, trafficability is good on the level to rolling coastal plains, hills, plateaus, terraces, and inter-mountain valleys. The mountains and areas of highly dissected hills and plateaus are unsuited for vehicle movement the year-round except over established routes.

General Weather. The transition from summer to winter takes place fairly rapidly in September and October as the Azores High weakens and mid-latitude westerlies establish themselves over the region. By the end of October the transition is complete. The intense summer solar radiation on the Mediterranean causes the water temperature to rise. As a result, when polar air masses move southward into the area in late fall, the sea surface is relatively warmer than air in the boundary layer. This causes instability and increases rainfall, especially on the windward slopes of the Atlas Mountains where orographic lifting also helps increase rainfall. Daily land and sea breezes in early fall condition the daily weather near the coast, but less so than in summer.

Sky Cover. Cloud ceilings occur 30-40 percent of the time at noon during October (Figure 3-29), the cloudiest month during fall. Most clouds near the Mediterranean coast are due to the instability caused by the lows and fronts that become more frequent through the season. Also, the warm ocean surface in the Mediterranean promotes instability and moisture transfer to the boundary layer. Ceilings less than 3,000 feet (900 meters) occur most frequently in the morning during September along the Atlantic coast (40-55 percent)--see Figure 3-30. The cold Canary current causes the stable conditions necessary to fog and stratus formation. These conditions improve during the day so that ceilings less than 3,000 feet (900 meters) occur 10-25 percent in the late afternoon. The western Mediterranean coast also has a higher frequency of ceilings below 3,000 feet (900 meters) in the morning. Cold water entering the Mediterranean via the Strait of Gibraltar has not sufficiently mixed with the warmer Mediterranean water. As a result, the water there is cooler than the air above it, causing stable conditions. Ceilings less than 3,000 feet (900 meters) are infrequent along remainder of the Mediterranean coast and on the Saharan side of the Atlas Mountains. The ocean-facing slopes of the mountains experience more cloud ceilings as the fall progresses towards winter. In general, the cloudiness decreases along the Atlantic coast while it increases along the Mediterranean coast

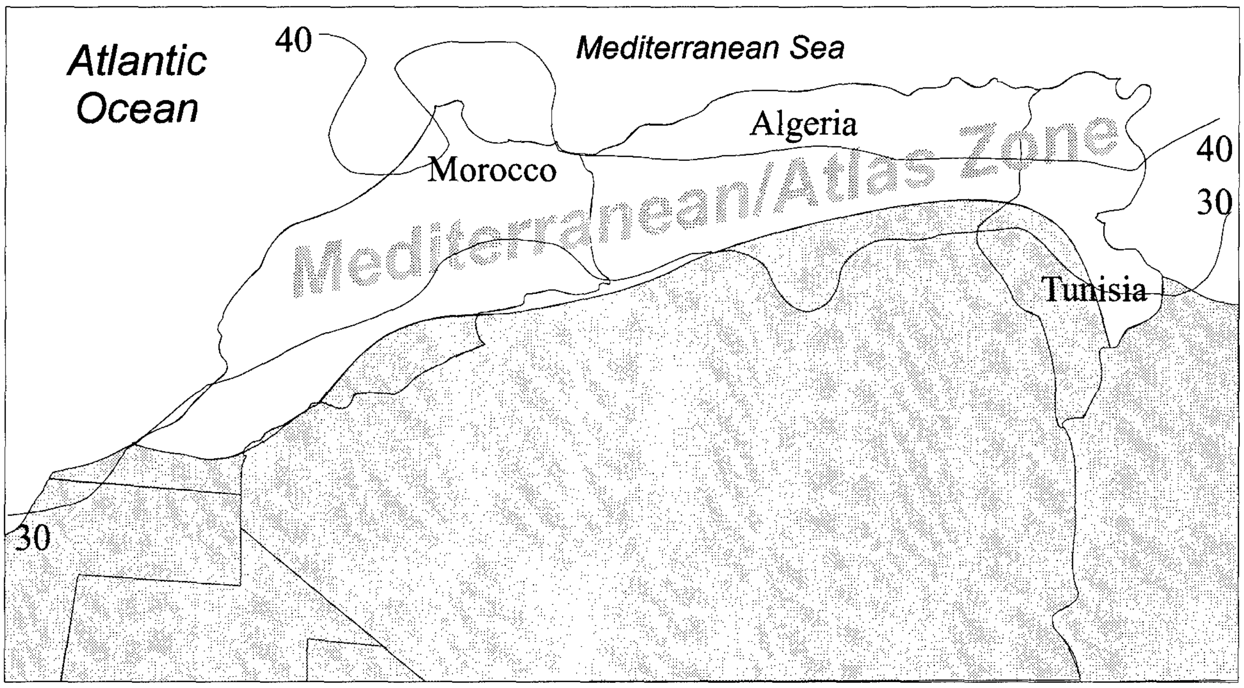


Figure 3-29. October Percent Frequencies of Ceilings. The isopleths represent the frequency of cloud ceilings at any altitude for local noon.

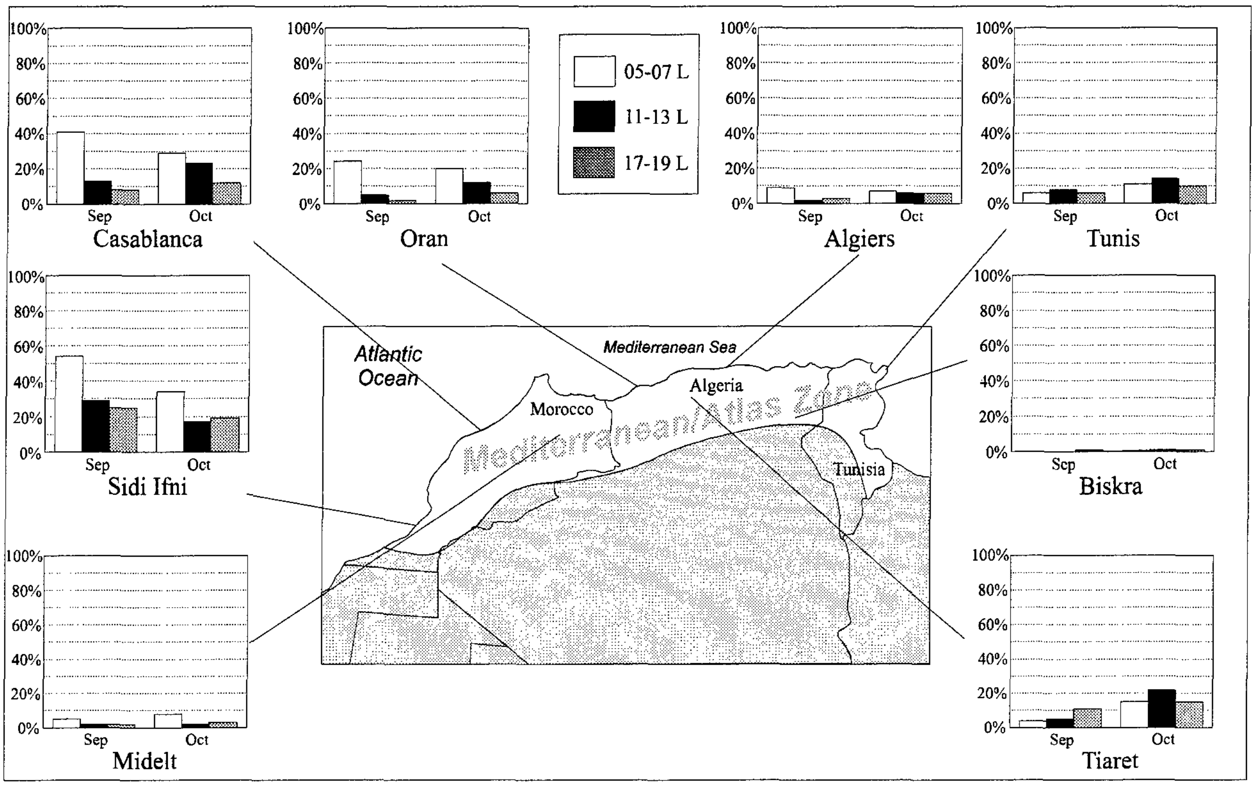


Figure 3-30. Fall Percent Frequencies of Ceilings Below 3,000 Feet (900 Meters). The graphs show a monthly breakdown on the percentage of ceilings below 3,000 feet (900 meters) based on location and diurnal influences.

Visibility. Visibilities are good, except along the coasts in morning fog and stratus that occur throughout the season (Figure 3-31). Along the Atlantic and Mediterranean coasts visibility less than 4,800 meters occurs between 10 and 20 percent of the time. By late morning, these visibilities usually improve to more than 4,800 meters as the percentage decreases to less than 5 percent. Elsewhere, less than 4,800 meters happens less than 5 percent of the time regardless of the time of day. Fog occurs 2-4 days per month along the Mediterranean coast and 4-8 days per month along the Atlantic coast. Blowing dust in the Saharan Atlas Mountains isn't as frequent as in summer at about 4 days per month.

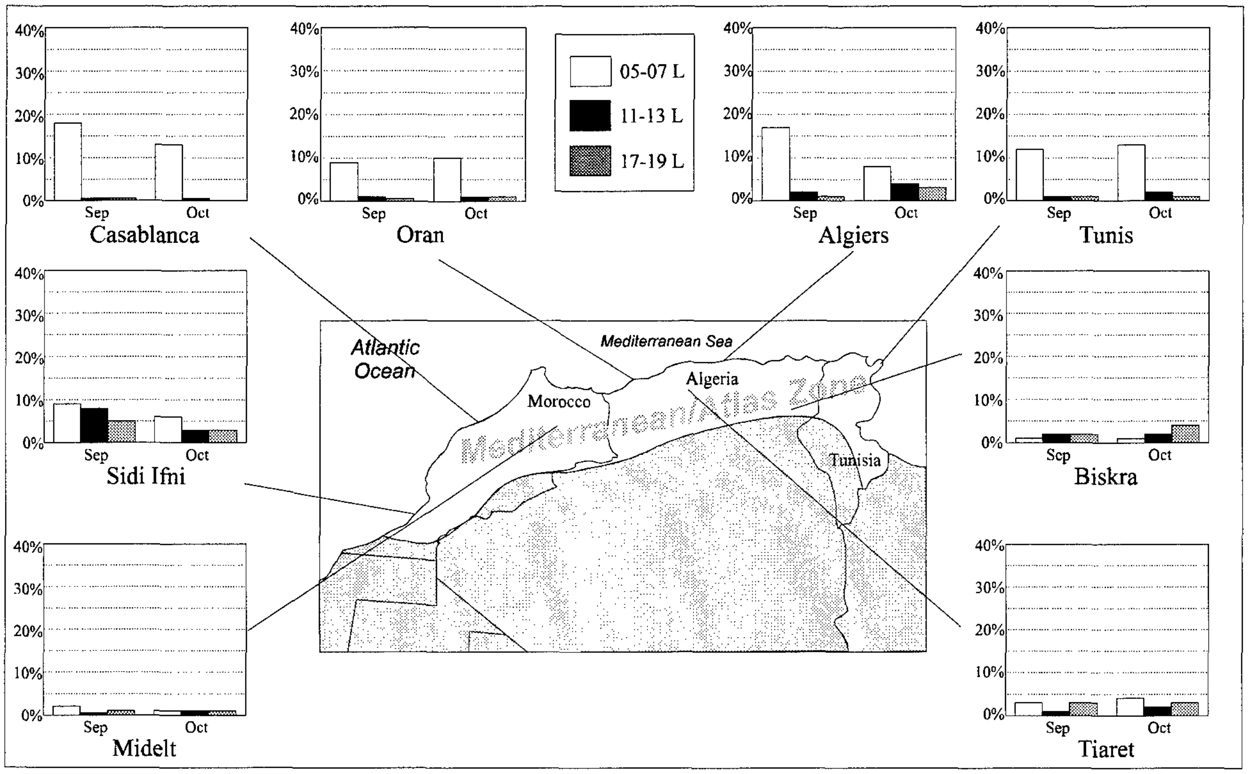


Figure 3-31. Fall Percent Frequencies of Visibilities Below 4,800 Meters. The graphs show a monthly breakdown on the percentage of visibilities below 4,800 meters based on location and diurnal influences.

Surface Winds. Until the end of October when the midlatitude westerlies predominate, local conditions still somewhat control the surface winds. The land/sea breeze still is in evidence on the surface wind roses for October (Figure 3-32) at some coastal locations. However, the sea breeze starts later in the morning than in summer and averages only 10-15 knots in the afternoon. The westerlies also are evident in that southwesterly winds have increased in frequency since July. The Mediterranean coast from Tangier to Tunis experiences about four siroccos per month. These cause a rapid change in the weather because sirocco air is at its hottest, and driest when it reaches the Mediterranean. October is a month of secondary maximum occurrence of siroccos during the year.

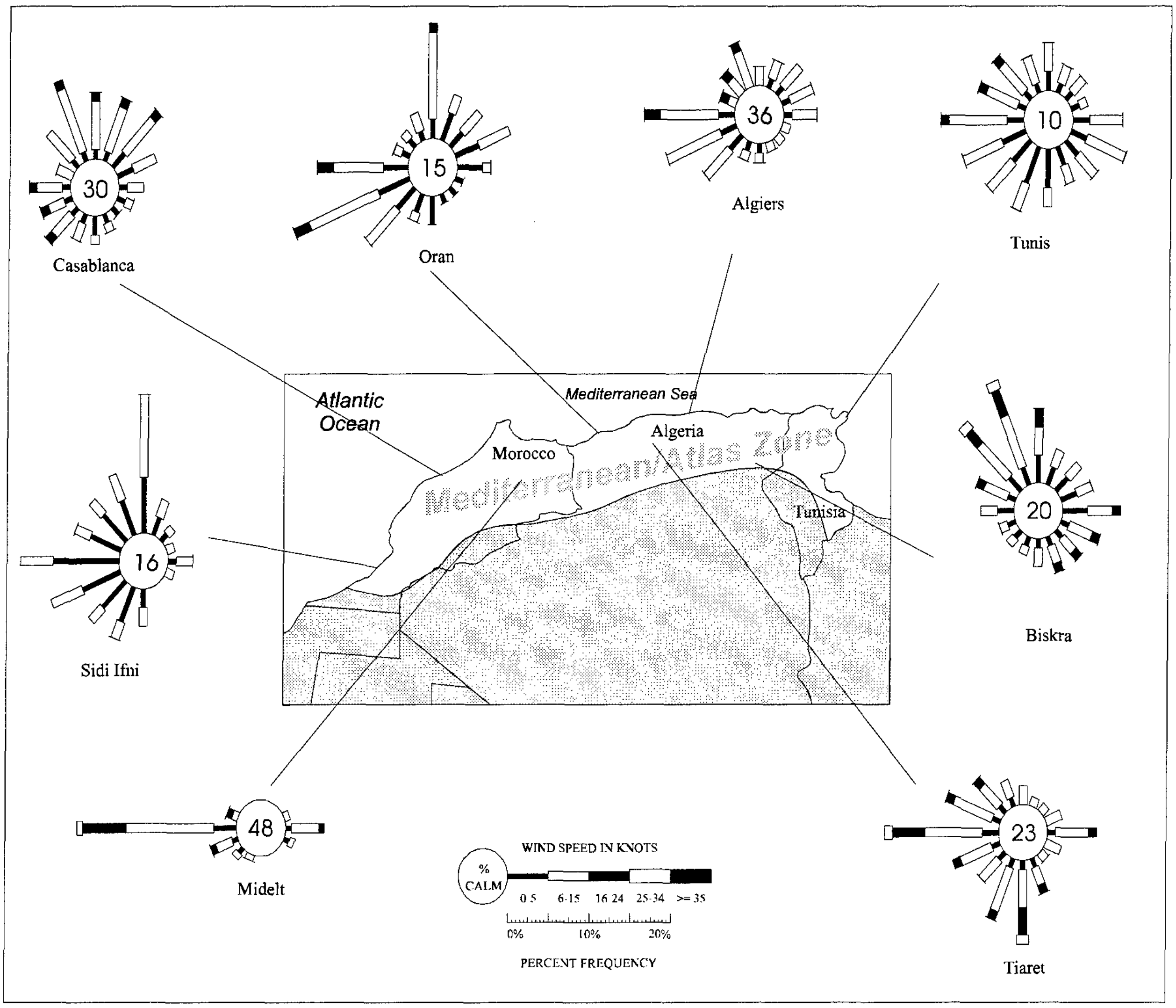


Figure 3-32. October Surface Wind Roses. The figure shows prevailing wind direction and range of speeds based on percent of frequency and location.

Winds Aloft. The subtropical jet migrates southward over the Mediterranean/Atlas Zone as it moves toward its mean January position as shown in Figure 2-7 (Page 2-12). Its speed averages only 30-60 knots during this part of the year. Figure 3-33 shows westerly winds at most levels at Algiers during October. Maximum speeds at 300 mb are less than 100 knots.

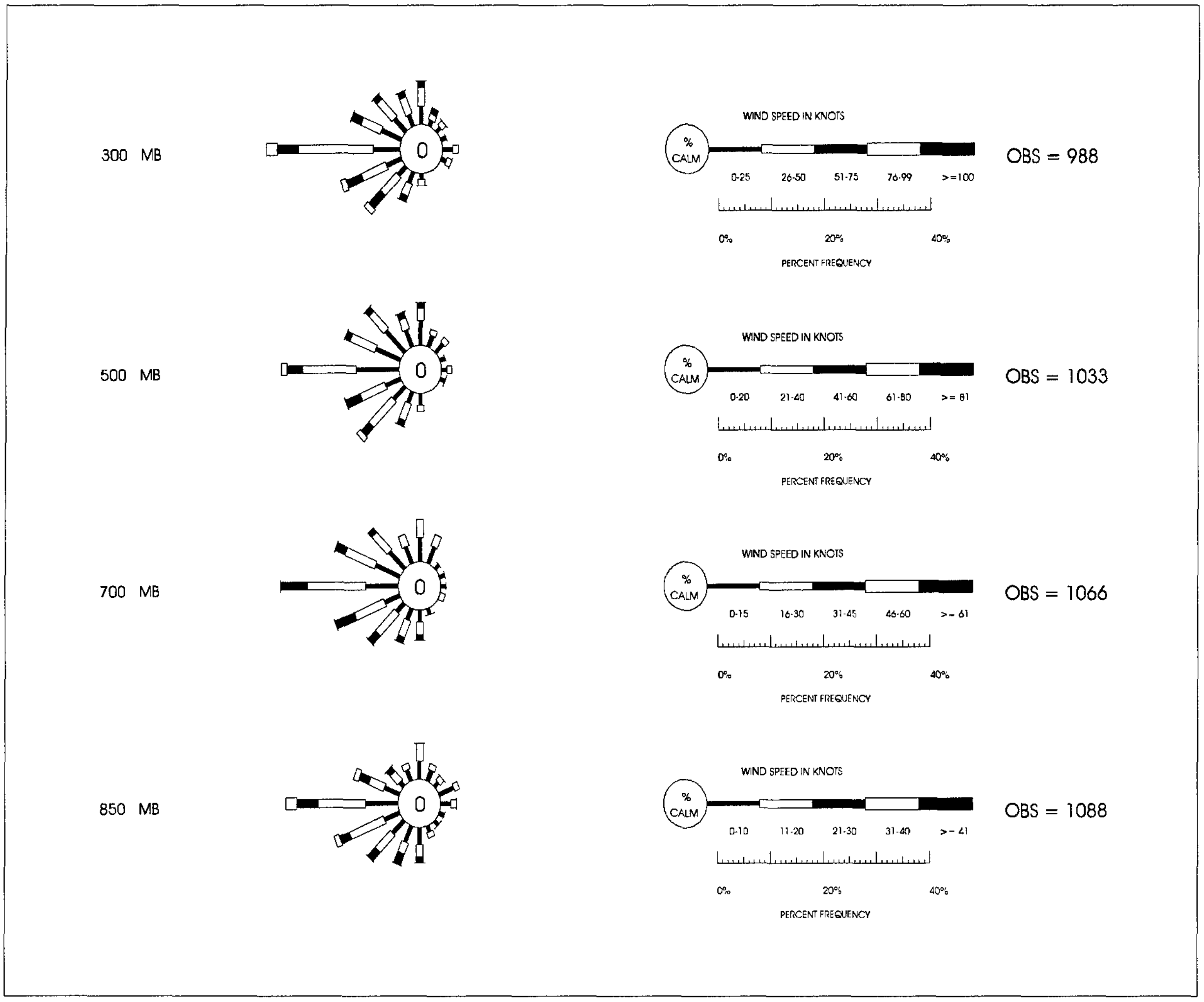


Figure 3-33. October Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Algiers, Algeria.

Precipitation. Rainfall increases through September and October nearly everywhere except in extreme southern Morocco due to the increasing frequency of Mediterranean Lows and polar fronts. Most of the Mediterranean coast receives 50-100 mm of rainfall during October, on average (Figure 3-34). Some locations average over 100 mm, especially in northern Morocco and near the Algeria-Tunisia border. Along the Mediterranean coast, rainfall days increase to 11 days at Algiers and Tunis in October (Figure 3-35). It snows in the High Atlas Mountains in Morocco in the fall.

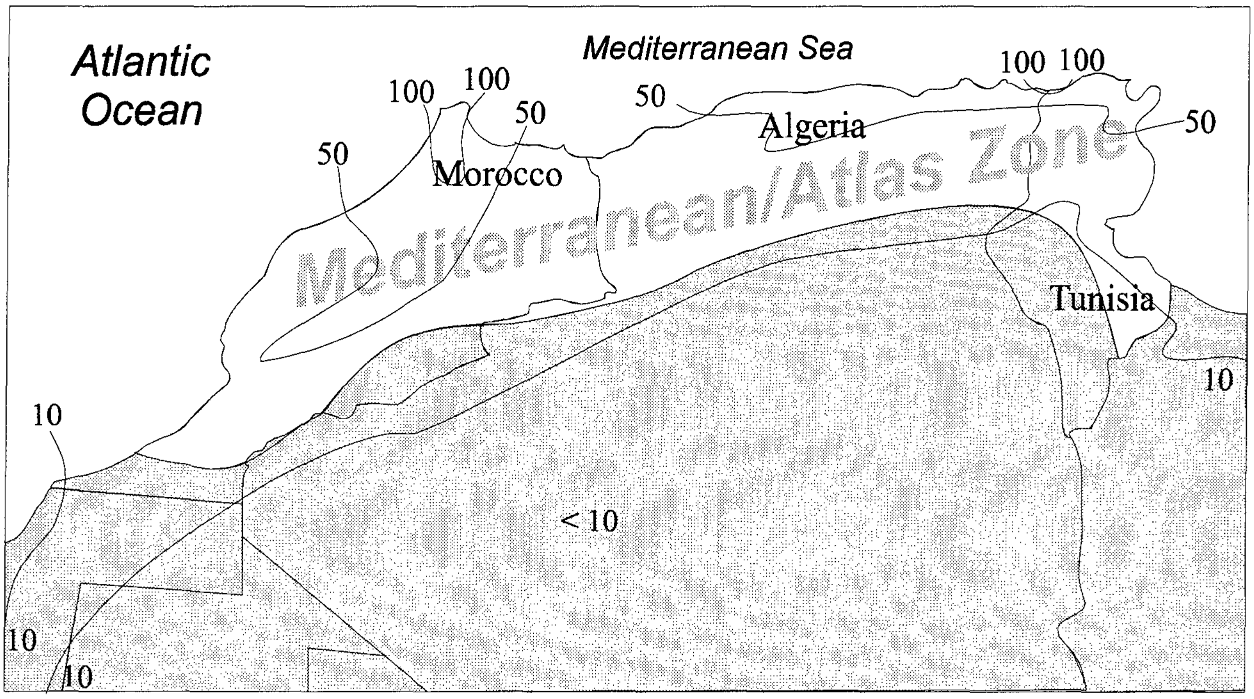


Figure 3-34. October Mean Precipitation (mm). The isopleths show two main precipitation areas: northern Morocco and the northern Algeria-Tunisia border.

Thunderstorms. At the same time that rainfall increases along the Mediterranean, thunderstorm frequency also increases there due to increasing instability; generally, they occur on about 5 days per month. Elsewhere, they occur less frequently (see Figure 3-35).

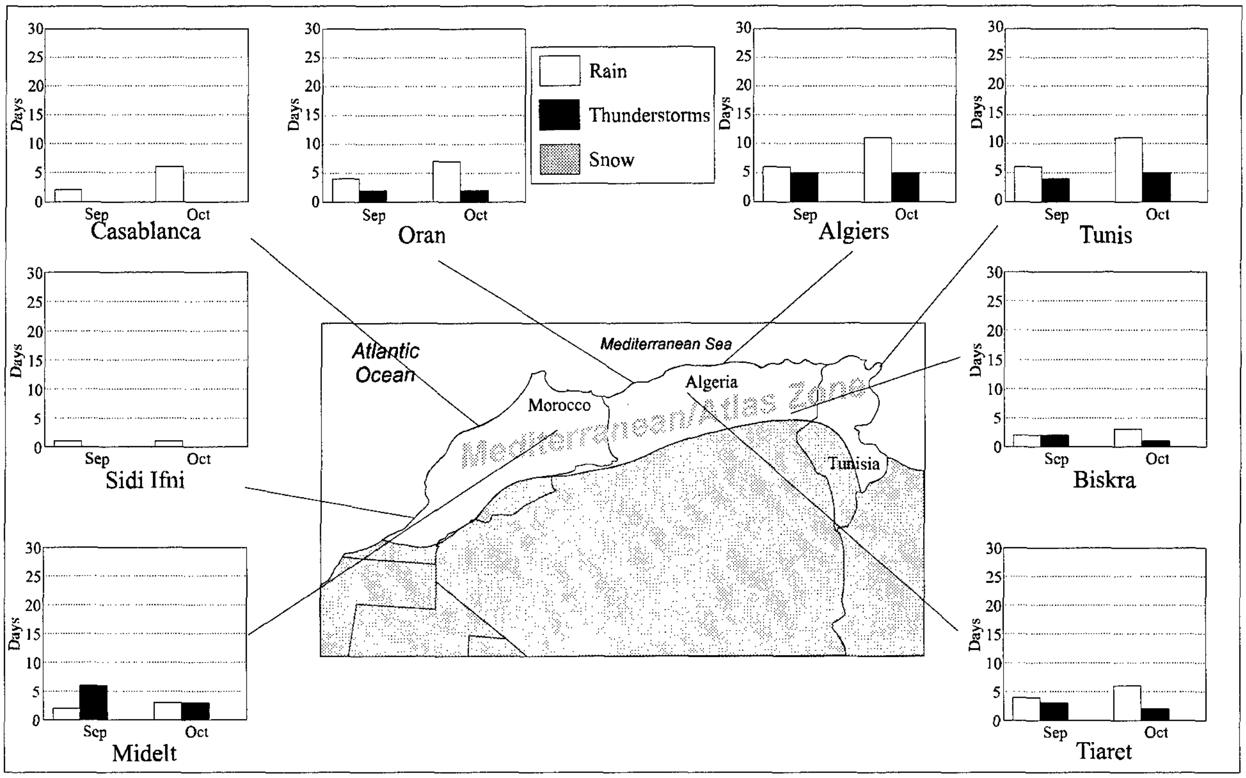


Figure 3-35. Fall Mean Precipitation and Thunderstorm Days. The graphs show the average fall occurrence of rain and thunderstorm days for selected cities in the Mediterranean/Atlas Zone.

Temperatures. While still hot at times during the fall, temperatures on average are lower than those of summer. Average high temperatures decrease so that in October they range from 23 to 25° C at most locations in the Mediterranean/Atlas Zone (Figure 3-36). At higher locations it's about 5°C cooler. Locations on the Sahara side of the mountains are several degrees warmer. Extreme highs exceed 40° C during September, but in October they reach 35-38° C. Average low temperatures also drop several degrees from September to October. They average 14-18° C in October with the warmest temperatures in southern Morocco (Figure 3-37). Higher elevations experience temperatures about 10° C colder. Extreme low temperatures go below freezing at elevations above about 3,280 feet (1,000 meters).

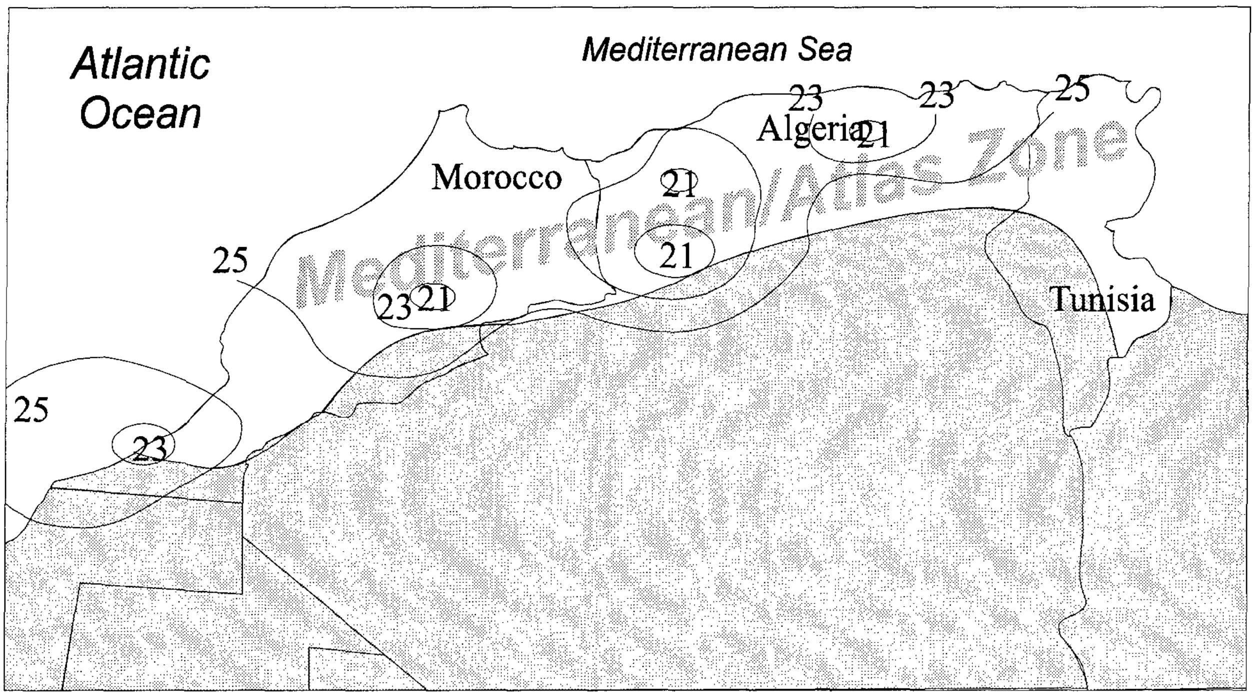


Figure 3-36. October Mean Maximum Temperatures (° C). These temperatures represent the average of all high temperatures for October. Daily high temperatures often will be higher than the mean. Mean maximum temperatures in September are higher.

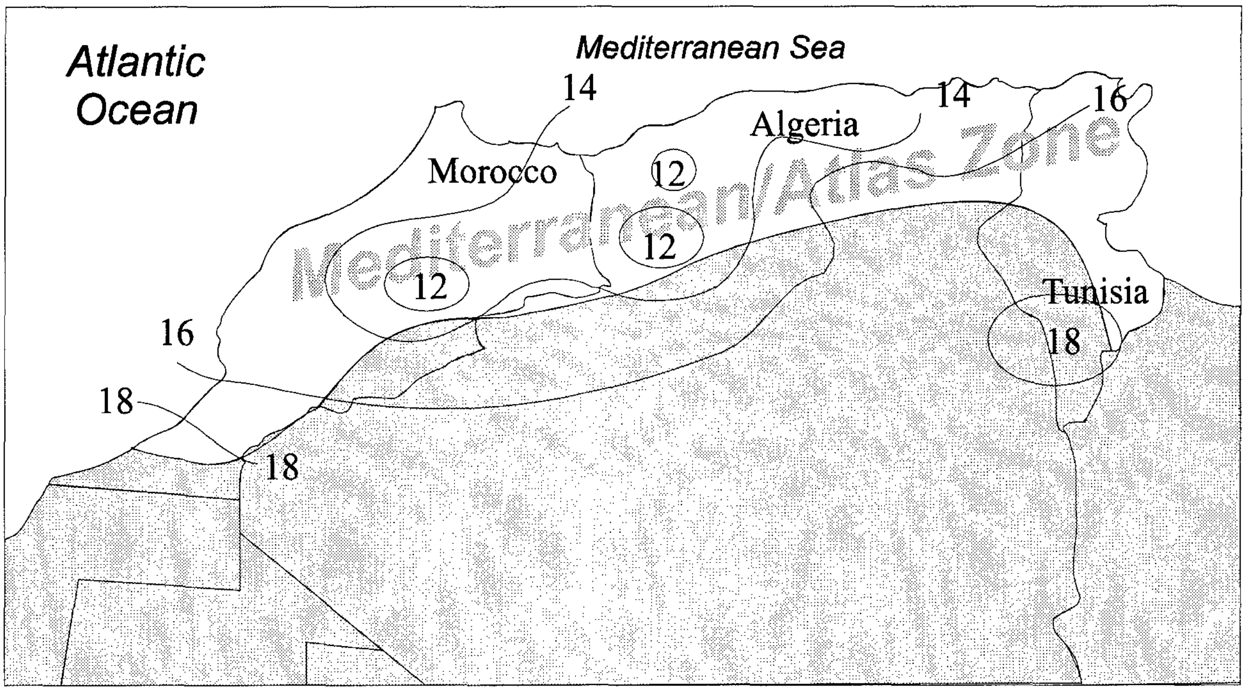


Figure 3-37. October Mean Minimum Temperatures (° C). Mean minimum temperatures represent the average of all temperatures for October. Daily low temperatures are often lower than the mean.

Hazards.

Aircraft Icing. Moderate or greater aircraft icing can occur in the layered clouds associated with the fronts and Mediterranean Lows that increase in frequency during fall, particularly in October.

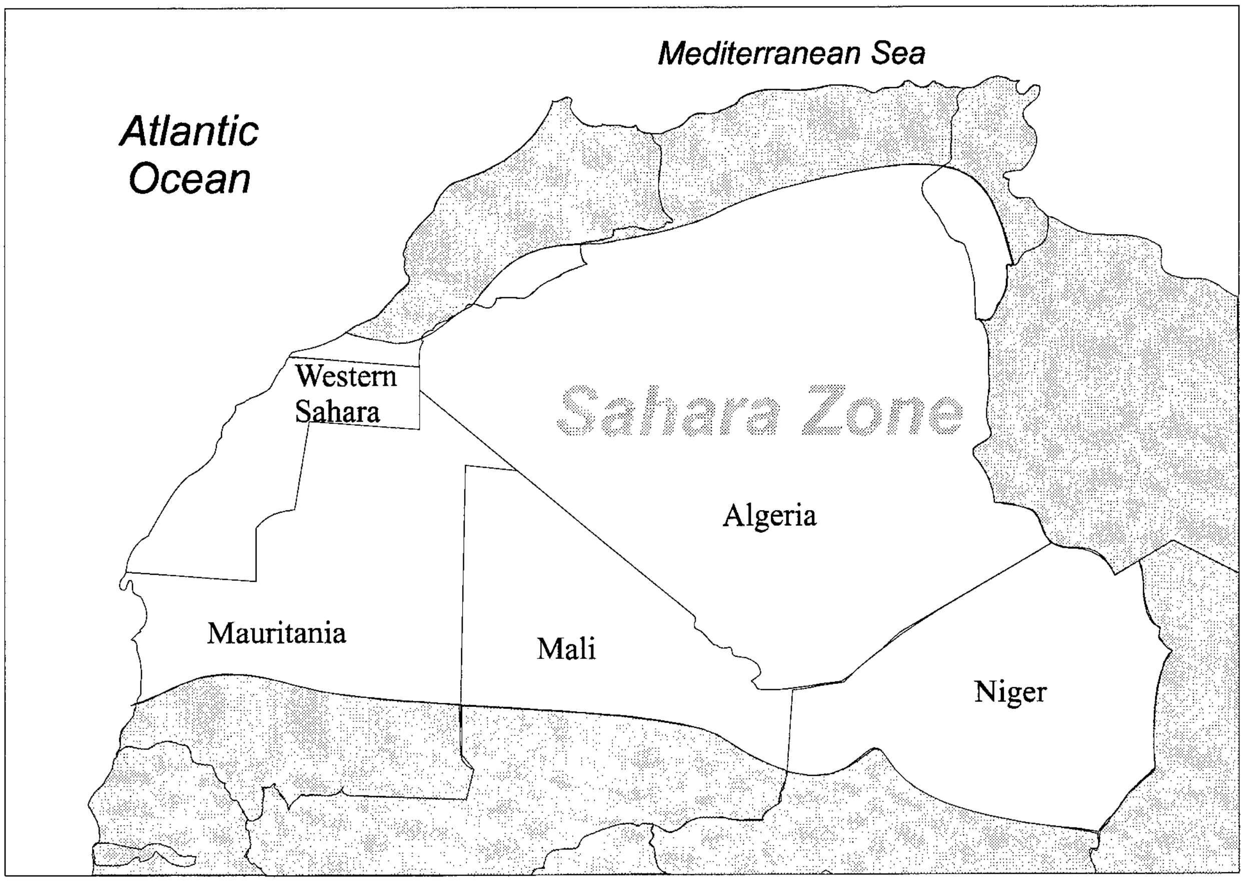
Turbulence. Moderate to severe turbulence in the vicinity of the mountains is a hazard during frontal passages and due to mountain wave turbulence. Due to the dryness in the atmosphere on the lee side of the mountains, the telltale clouds normally associated with mountain waves may not develop.

Trafficability. The good trafficability of the summer deteriorates with the increasing rainfall of fall. While it may remain good in September, in October it may become poor in the coastal plains, hills, plateaus, terraces, and inter-mountain valleys. The mountains and areas of highly dissected hills and plateaus are unsuited for vehicle movement the year-round except over established routes.

Chapter 4

THE SAHARA ZONE

This chapter describes the geography, major climatic controls, special climatic features, and seasonal weather for the Sahara, an arid zone between the Sahel and the Mediterranean zone. It consists of the northern parts of Niger and Mali, the southern two thirds of Algeria, southern Morocco and Tunisia, including the coastal regions of Western Sahara and northern Mauritania.



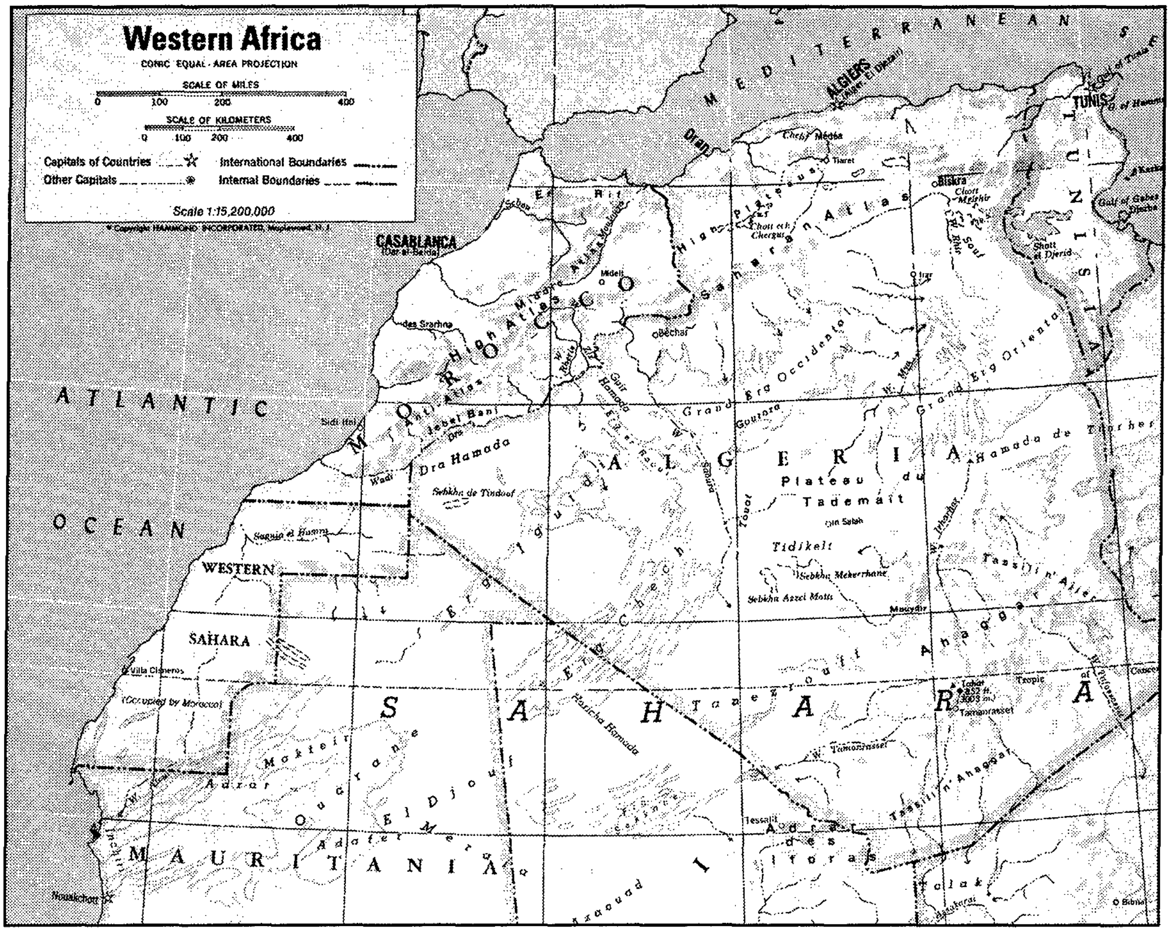


Figure 4-1. Topography of the Sahara.

Seasons. There are two seasons in the arid Sahara Zone — summer and winter. The summer season runs from March through September and the winter season runs from October through February.

Boundaries. The northern border of the Sahara is defined by the southern edge of the Atlas Mountains and the line at which average annual rainfall decreases to less than 100 mm. The southern boundary marks the line at which annual rainfall equals 250 mm and coincides with the northern boundary used in the Equatorial Africa regional climatology study (USAFETAC/TN—95/001). The Atlantic Ocean borders the region on the west and the countries of Libya and Chad border it on the east.

Terrain. The elevation of the Sahara Zone lies predominately between 700-1,600 feet (200-500 meters) above sea level (see Figure 4-1). Along the coastline of Western Sahara and Mauritania, elevation drops below 100 meters. Elevations south of the Atlas Mountains and around the Ahaggar Mountains rise to between 500-1,000 meters. The elevations of Chott (Shott) Melrhir and Chott (Shott) Jerids in northeast Algeria and Tunisia drop to 100-200 meters below sea level.

Scattered across the Sahara are regions of deep rolling sand dunes called: ergs or sand seas. Ergs, oriented northeast to southwest, reflect the predominate northeasterly flow pattern that affects the region. These regions occupy about 15-25 percent of the Saharan Desert. Dunes may reach a height of 150 meters while the mountainous sand ridges of the ergs may reach as high as 300 meters. The remainder of the Sahara is composed of extensive gravel covered plains (reg) and rocky desert (hammada).

One of the most prominent relief features of the Sahara is the Ahaggar Mountain region in southeastern Algeria. Mount Tahat is the highest peak at 9,571 feet (2,918 meters). The Air Massif in northern Niger and the Iforas Massif in northeastern Mali are extensions of the Ahaggar Mountains with peaks near 3,280 feet (1,000 meters).

Rivers and Drainage Systems. No rivers flow through this region. Drainage consists of an extensive network of wadis which are dried up stream beds that originate in the higher elevations of the Atlas and Ahaggar Mountains. Some of these wadis are seasonally active while others are the remnants of a single storm. Wadis in the Ahaggar Mountain region are most active during June-September. Wadi Saoura, in northwest Algeria, and the Wadi Dra along the border of Morocco and Algeria are two of the more prominent wadis originating from the Atlas Mountains. Smaller wadis drain into chotts (or shotts), which are shallow depressions that surround a salt marsh. These salt marshes tend to dry up during the long absence of preciptation that occurs in the Sahara. Sand dunes may also store significant quantities of rainwater with seeps and springs emanating from various escarpments in the desert.

Vegetation. Vegetation in the Sahara is sparse. Scattered concentrations of grasses, shrubs, and trees exist in the highlands, oases, and along wadis. Heat and drought tolerant grasses—herbs, small shrubs and trees—are found on the plains and plateaus. Many herbs are short-lived and germinate within 3 days of adequate rainfall and sow seeds within 10-15 days. Woody plants such as olive, cypress, and mastic trees grow in the Saharan highlands, while salt tolerant grasses and plants grow along the west coast.

MAJOR CLIMATIC CONTROLS OF THE SAHARA ZONE

Ocean Currents/Sea-Surface Conditions. The Sahara Zone includes the Atlantic coastline; the discussion in Chapter 2 applies to the region. Figures 2-1 and 2-2 show the major ocean currents affecting the region and the mean sea-surface temperatures. The cold Canary Current modifies the influence of the Harmattan, a northeasterly surface wind, producing a humid but temperate climate along the coast. The cooling affect of the ocean is enhanced along the Atlantic coast, where persistant northeasterly winds produce upwelling of relatively cool water within the Canary Current. This affects all of the Atlantic coastline north of 20° N. Of interest, is the pseudo cold front created along the coast of Western Sahara where upwelling is at its strongest. This front is caused by cold ocean currents and strong upwelling, which creates a sharp temperature discontinuity between offshore and onshore temperatures. The result is a semipermanent layer of stratocumulus clouds that ends abruptly at the coast. Cold waters stabilize the boundary layer along the Atlantic coast leading to development of stratiform clouds, fog, and haze. Modified temperatures, increased relative humidities, and an increase in cloudiness are the result of onshore flow of the cooler maritime air. The current averages about 0.5 knots throughout the year. A little more than 0.5 meters differentiates high from low tides along the coast.

Azores High. This high pressure cell is a very important part of the atmospheric circulation for the Sahara. The Azores High migrates north in the northern hemisphere summer, which prevents frontal systems from reaching the northern Sahara. During winter, the high moves south and ridges into Western Sahara and Mauritania, allowing the Harmattan to dominate the Sahara. This migration south also allows cold fronts to invade the northern Sahara, accounting for the sparse precipitation received during the winter.

The South Atlantic High. This cell migrates north during the Northern Hemisphere summer providing the southern Sahara with its southwest monsoon. During winter, this high moves back to the south and does not affect the Sahara.

The Saharan High. This cell esists only between frontal passages. Its strength is enhanced by strong radiative cooling. The Saharan High is strongest during the winter (Figures 2-3a and 2-3b) and does not show up on the chart for July. It's generally located in the northern sections of the Sahara and the outflow from this high generates the hot, dry, dust-laden wind known as the Harmattan. This high is replaced by the Saharan Heat Low during the summer.

The Saharan Heat Low. The persistant circulation associated with the Saharan Heat Low is responsible for the introduction of large amounts of dust into the air. Furthermore, the low is responsible for the extremely low humidities, large daily temperature variations, reduced visibilities, and the clear skies that typify the Sahara. Winds with the Saharan Heat Low are usually of diurnal nature, averaging 10-15 knots during the afternoon hours and decreasing to light and variable after sunset. Wind directions are predominatly northwest through northeast in the northern sections of the Sahara and south through southwest in the southern Sahara.

The Near EquatorialTradewind Convergence (NETWC). The NETWC affects the southern Sahara from July - September. Its mean summertime position is 20° N, but has moved as far north as 23° N. It brings the southern Sahara nearly all of its annual rainfall. During the summer season as the NETWC moves north, surface winds become southwesterly and draw moist Atlantic air over the southern Sahara. African squall lines are frequently generated in the moist, unstable air mass south of the NETWC's surface position. The summer season ends when the NETWC retreats south of the Sahara to its mean annual winter time position of 10° N.

SPECIAL CLIMATIC FEATURES OF THE SAHARA ZONE

Harmattan/Harmattan Haze. "Harmattan" is the name given to the northeasterly surface wind that blows throughout the winter season, although, it can occur any time of the year depending on the location of the NETWC. The Harmattan may extend southward to 5° N in January and to about 18° N in July. The dust and haze that accompany the wind is called "Harmattan Haze." Outflow from the Saharan High generates these winds. The Harmattan is hot and dry during the day, but becomes cool at night due to radiational cooling. Visibility is often poor during the winter season because of the dust and haze. During winter, the Harmattan dominates the entire Sahara with the largest amounts of dust and haze originating over Algeria. In summer, only the northern portions of the Sahara are affected as the Harmattan shifts northward with the Azores High.

African (or Tropical) Squall Lines. African squall lines commonly called "disturbance lines," or "easterly waves," are the most important factors in the production of rainfall during the southern Sahara summer south of 20° N. They are well organized, solid bands of thunderstorms that propagate west at 17-45 knots. These squall lines are oriented north to south and are preceded by a layer of cirrus or altostratus and altocumulus. Wind shifts are commonly from southwest to northeast and can become very violent behind the line of storms. Abrupt temperature drops and a gradual lowering of the ceiling can also be expected. Gustiness usually lasts from 30-60 minutes and then a gradual decrease of winds will occur. North of 20 degrees, these lines of thunderstorms produce brilliant lightning shows, but very little moisture. Early in the summer season (April and May), these storms may produce what is commonly called a "Dry Tornado." A dry tornado is nothing more than dust lifted from the desert by intense thunderstorm winds. Such winds may reach downburst strengths — over 80 knots have been recorded.

Land/Sea Breezes. The Azores High greatly impacts the land and sea breeze of the Atlantic coast. Winds blow parallel to the Atlantic coastline minimizing sea breeze penetration into Western Africa. The Harmattan blows throughout the year, which can have an offsetting effect for the sea breeze. The dry continental air blows off the Sahara and mixes with the moist-laden Atlantic air, minimizing cloudiness along the sea breeze front. The sea breeze normally only penetrates 20 - 40 km inland and may bring low stratus, decreased visibilities, and light precipitation. The sea breeze is most prominent from June to August when the land and water temperature contrast are the greatest. Also, the year long upwelling of cold water, along the coast, maintains higher pressure over the sea than over the land inhibiting the land breeze and enhancing the sea breeze. The land breeze has a tendency to become stronger in winter due to the strengthening of the Saharan High.

Mirages. Abnormal refraction in the atmosphere may cause a mirage. Two types of mirages can occur in the Sahara. Inferior mirages, in which a portion of the blue sky is reflected downward and appears as a distant lake, are common. This type of mirage is most likely to occur over the desert during the heat of the day when the surface air density increases sharply with height. Superior mirages, in which objects beyond the horizon appear at or above the horizon, are less common. In the interior, this type is most likely to occur during the cool of the early morning, when the air density decreases sharply with height. It may also occur along the coast during the day when cool air flows onto the land. Mirages can severely impair horizontal visibilities, particularly when the density differences are near the surface. Mirages can cause problems for pilots during takeoffs and landings because they can affect both horizontal and slant range visibility.

SPECIAL CLIMATIC FEATURES OF THE SAHARA ZONE

Chili. In north-central Algeria (southeast of the Atlas Mountains), local sandstorms and duststorms are not as common as they are farther south. However, a more widespread condition, known locally as a Chili, may affect this region. It is an excessively hot, dry and often dust-laden southerly wind that forms ahead of Atlas Lows. They occur most frequently from March to June, when increases in wind speed cause conditions to become unpleasant for 4 or 5 days a month. Chilis can last as long as 24 hours. Chilis, when they move north of the Atlas Mountains become known as Siroccos.

Atlas Lows. Atlas Lows form in north central Algeria and cross the northern Sahara with their associated cold fronts. They develop most frequently from March through May, but can occur anytime of the year. When the southerly or southeasterly winds associated with the Atlas Low are strong they generally produce a duststorm or sandstorm. These storms are well organized sand and duststorms that form a wall that closely conforms to the shape of the cold front that produced it. The particles are driven by violent vertical motions that lift the wall of sand to an altitude of 6,600-9,800 feet (2,000 - 3,000 meters). Sandstorms can stretch over a length of 50 - 150 km and have an average width of 30 - 60 km, although widths of 100 km are possible. The frontal systems move eastward at speeds of 16 - 45 knots. Strong wind gusts, severe turbulence, and visibilities near zero are possible with these storms.

Atlas lows generate very little cloudiness in the Sahara. Usually only scattered mid- and high-level clouds are capable of making it across the Atlas Mountains. Occasionally, the frontal systems associated with the lows are able to tap low-level moisture from the Atlantic Ocean. When this occurs, low clouds, precipitation, and low visibilities develop along the coast of Western Sahara and Mauritania.

General Weather. The climatic elements most commonly affecting the Sahara are precipitation (or lack of precipitation) and temperature. The NETWC moves northward with the onset of northern hemisphere summer driving the dry Saharan air northward. During the height of the summer monsoon (June-September) in the southern Sahara; the monsoon replaces the Harmattan 3-4 times a week. The NETWC, responsible for much of the weather in Equatorial Africa becomes weaker and much less distinct the further north it goes. At 20° N the NETWC becomes so weak that cloudiness and/or precipitation is usually nonexistent. The southern Sahara receives most of its sparse cloudiness and precipitation during the summer season. Due to the extreme aridity, the evaporation rate is twice as great as the precipitation rate leaving the Sahara with a moisture deficit. What rainfall that is received is seldom continuous and usually associated with isolated air mass thunderstorms or more organized African squall lines.

Drought is considered a normal occurrence. Drought in the north occurs all summer long with short but brief periods of precipitation. In the south, there are long periods of dryness broken into short rainy periods. In some years, more severe droughts occur when the NETWC does not travel as far north (leaving most of the southern Sahara under the influence of the Harmattan). Rainfall estimates indicate deficiency periods of 6-10 months along the coast and mountainous areas to 2 years in the interior desert regions. The southern Sahara receives the majority of its precipitation in July and August with the passage of the NETWC. Fronts trailing from the Atlas Low that cross the northern desert regions produce most of the sparse precipitation during the latter parts of the summer season and in early winter in the northern Sahara.

In summer, temperatures generally range from lows of 20-25 to highs near 40-50° C. Temperatures in the southern Sahara are somewhat modified because of the increased cloudiness and scattered showers that occur. Maximum temperatures reach their peak in May and June just prior to the onset of the NETWC. July is the month of maximum temperature for the northern Sahara. Temperatures of 55° C have been reported; however, because of sparseness of reporting stations, temperatures up to 60° C are likely. Along the coast, maximum temperatures are recorded in late summer due to the profound effects of maritime influences. It can take several months for the Atlantic Ocean to become heated enough for maximum readings to be recorded.

Summer ends as the Azores High and the South Atlantic High weaken and migrate south. This shifts the NETWC back to the south of the region. The Saharan High then strengthens and the Harmattan dominates the area.

Trafficability. Except for the mountainous regions (Atlas and Ahaggar) and the southern Sahara region affected by the NETWC, trafficability changes little from season to season. Trafficability is a measure of the capacity of surface soil to support moving vehicles. The capacity of soil to withstand traffic is a function of soil strength. This in itself depends on the combined effect of grain size and shape, organic matter content, mineral composition, plasticity, density, and moisture content. The Sahara is dominated by coarse-grained soils, large areas of high elongated sand dunes, sand sheets, drifting sand, broad-level sand and gravel plains. Flat-topped and highly dissected plateaus, and many boulder-covered areas, including the Ahaggar Mountains also dominate the Sahara. Summer in the Sahara brings showers to the southern regions and along mountains, and brings infrequent squalls to the southern coast. Although rainfall is usually meager, occasional violent downpours result in flash floods. The number of dry stream beds (wadis) is tangible evidence of this phenomenon. At times these floods are caused by a heavy rain that is beyond visual range, and the first or perhaps the only indication may be the approach of water in the stream beds. Strong squalls (strong winds and precipitation) can wash out roads and bridges, hindering trafficability in the Ahaggar Mountains and along coastal areas. In summer, flash flooding has its highest potential in the southern Sahara including the southern coastal region and the Ahaggar Mountains. Contributing factors to flooding are the hard, rocky soil that reduces water percolation and the lack of absorbency by the sandy surfaces of the Sahara.

Off-road vehicular movement is good to excellent year round on the broad-level sand and gravel plains, and flat plateau surfaces. Movement is poor in dune areas, highly dissected areas, and areas of deep and drifting sand. South and east of the Ahaggar Mountains are areas of extensive plateaus. Steep, rugged hills dissect many of these plateaus and movement would be very slow and winding. Mountains, extensive margins of plateaus, and boulder-covered areas restrict movement to existing routes.

Sky Cover. Cloud cover is generally sparse in the Sahara due to the continental air mass that dominates the area. Mean annual cloud cover averages less than 40 percent with a minimum cloud amount over Mauritania and Algeria of 15 percent. Figure 4-2 shows that most cloud cover received is in the southern Sahara with the progression of the NETWC northward. The majority of cloudiness is blocked by the Atlas Mountains in the northern Sahara. Clouds are usually high-based and ceilings are usually not lower than 8,000 feet. Isolated stratus occurs along the coast with bases from a few hundred feet to 2,000 feet.

Coastal areas receive most of the cloud cover during the summer season, particularly from July through September, due to the increased temperature difference between land and water. Low stratus associated with the cool Canaries Current occurs mostly during the early morning hours from April through September. The coastal city of Villa Cisneros has a dramatic increase in clouds in the summer due to the oceanic influence, and the cool northerly flow behind developing Atlas Lows. Inland cloud cover occurs less than 30 percent of the time (Figure 4-2). The southern Sahara receives cloud cover 30-50 percent of the time due to the migration of the NETWC northward.

At the coastal stations of Villa Cisneros and Nouakchott, during the peak months of July and August, morning ceilings less than 3,000 feet (900 meters) occur 20-40 percent of the time (Figure 4-3). At Villa Cisneros ceilings less than 1,000 and 500 feet (300 and 150 meters) occur approximately 30 percent and 10 percent of the time, respectively. While at Nouakchott, 1,000 and 500 feet (300 and 150 meters) ceilings only occur 7 percent of the time combined. This is because Villa Cisneros is not blocked by terrain features and receives a more oceanic influence.

In the heart of the Sahara ceilings less than 3,000 feet (900 meters) occur less than 10 percent of the time. Peak frequencies occur at Tamanrasset and Tessalit, due to the affect of the Ahaggar Massif and the migration of the NETWC northward. These lower ceilings occur primarily on summer afternoons due to increased convective activity.

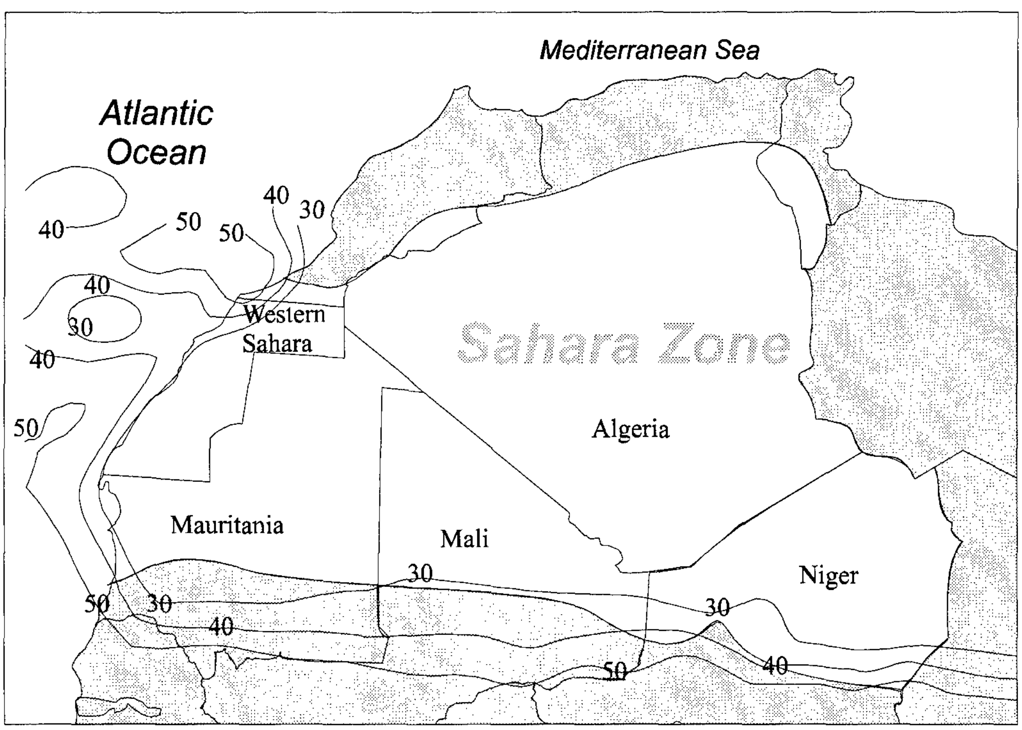


Figure 4-2. Percent Frequencies of Ceilings. The isopleth lines show the impact of the ocean currents and the NETWC on the frequency of ceilings within the Sahara Zone.

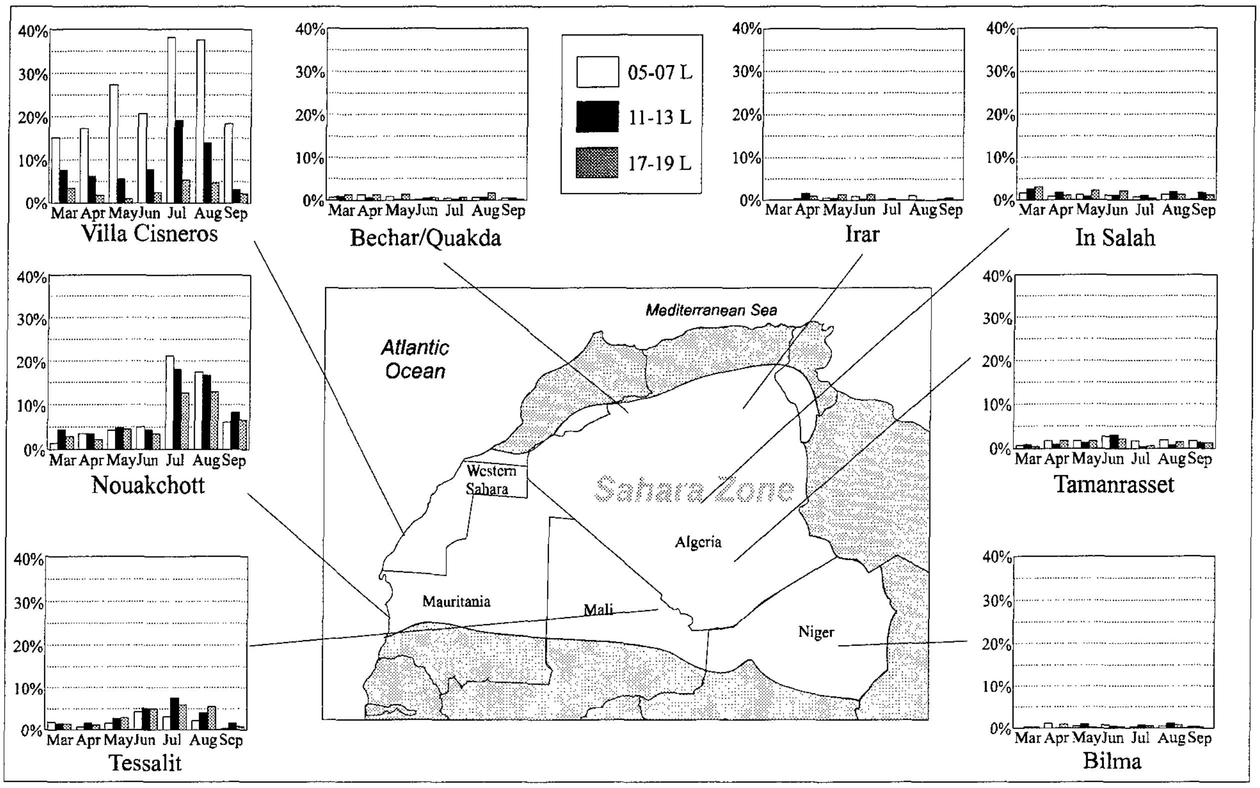


Figure 4-3. Summer Percent Frequencies of Ceilings Below 3,000 Feet (900 Meters). The graphs show a monthly breakdown on the percentage of ceilings below 3,000 feet (900 meters) based on location and diurnal influences.

Visibility. Harmattan haze, blowing sand, dust, and occasional fog problems along the coast and Ahaggar Mountain areas are the elements that most influence visibilities in the Sahara. With the NETWC dividing the Sahara, much of the surface-based dust is lifted into a haze layer (Harmattan Haze) in the extreme southern portions of the Sahara. This Harmattan haze reduces visibilities to approximately 10-13 km. Under extreme conditions, visibilities may be reduced to less than 450 meters; slant range visibility could go as low as 450 meters. The Harmattan haze north of the NETWC has an average depth at 8,000 feet, 2.4 km, but can reach 12,000 feet deep (3.6 km) and be carried great distances by the upper level winds. South of the NETWC, the dust and haze usually extends from 3,000 to 6,000 feet (900 to 1,800 meters) in the air. Consequently, visibilities aloft are poor, while surface visibilities are good. Although haze can persist throughout the day, it reaches a maximum during the afternoon when instability is at its greatest. Harmattan haze conditions can persist for 2 to 5 days. The principle cleansing mechanism for this haze is precipitation.

Fog, while not as frequent as the Harmattan haze, has a higher frequency along the coast. The strengthening of the sea breeze and temperature contrast between land and water help increase occurrences of fog along the coast. The north coast, with no blocking terrain features, has a higher frequency of fog than the south coast. Most fog generally develops around sunset and lasts until midmorning.

As seen in Figure 4-4, visibilities below 4,800 meters occur during all hours, but the lowest visibility occurs during afternoons when turbulent mixing is at its greatest. Nouakchott has the greatest frequency of reduced visibilities during May when visibility drops below 4,800 meters 50 percent of the time. Visibilities less than 1,600 meters occur 15-20 percent of the time. Even though occasional fog occurs, sand and dust cause the majority of the visibility problems. A good example of this is along the coast; Nouakchott receives only one day of fog and 21 days of blowing sand during May.

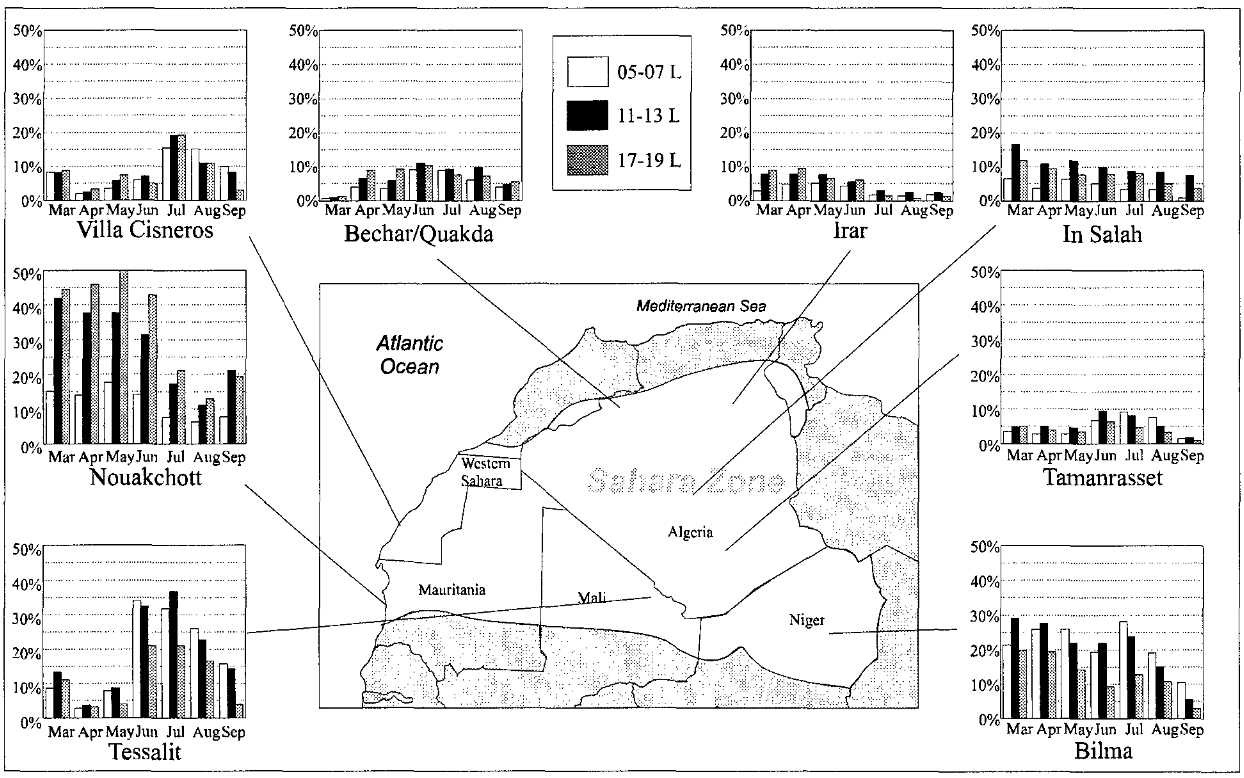


Figure 4-4. Summer Percent Frequencies of Visibilities Below 4,800 Meters. The graphs show a monthly breakdown on the percentage of visibilities below 4,800 meters based on location and diurnal influences.

Surface Winds. Surface wind directions are predominately from the northeast in the northern half of the Sahara, reflecting the influence of the Azores High. The dominant flow along the coast is parallel to the coastline. The sea breeze assists in bending the predominate flow to the northwest in the lower layers. Typical summer sea breeze wind speeds average 10 - 15 knots. Wind directions are primarily from the southwest in the southern Sahara reflecting the influence of the NETWC. Bechar/Quakda winds usually favor the south due to valley winds created by the summer time heating of the Atlas Mountains.

Mean wind speeds are normally less than 16 knots at most locations (Figure 4-5). Along the coast, mean wind speeds may be higher due to the influence of the Azores High and the absence of blocking terrain features. For example, wind speeds at Villa Cisneros are generally between 16 and 24 knots, but greater than 35 knots are possible. Villa Cisneros is one of the few locations not blocked by mountains or other land forms.

Gale force winds (27-48 kts) occur more frequently along the coast of Western Sahara than inland regions. The Atlas Low that deepens in central Algeria creates a higher potential for strong winds. Villa Cisneros has 72 days annually with surface wind speeds over 27 knots; 8-15 days a month occur from April through August. At most locations in the interior, there are less than 5 days annually with winds over 27 knots. Nearly all locations have reported wind speeds greater than 35 knots. Villa Cisneros and Tessalit both have recorded extreme wind speeds of 74 knots.

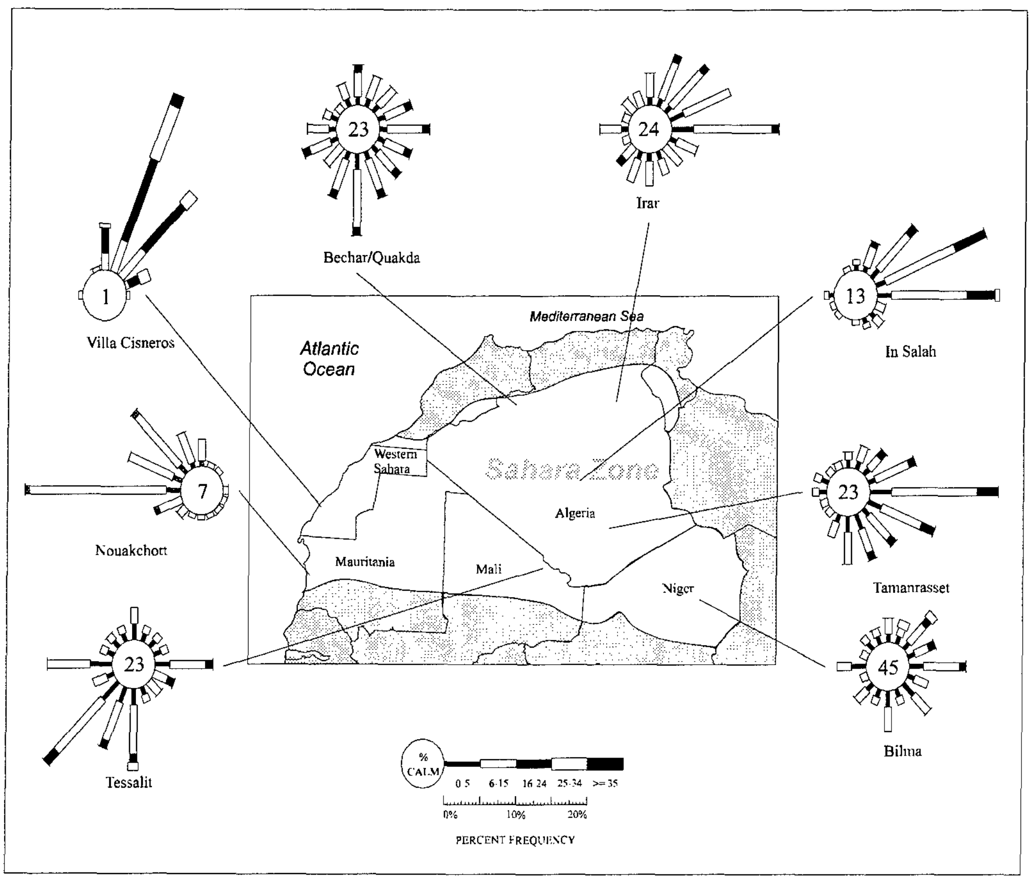


Figure 4-5. August Surface Wind Roses. The figure shows the prevailing wind direction and range of wind speeds based on frequency and location.

Winds Aloft. The STJ rarely penetrates the Sahara during the summer and is usually located in the northern Mediterranean area and the PFJ is all but nonexistent. Flow is generally from the east through northeast up to 700 mb (see Figures 2-11 through 2-14 and figure 4-6). The westerly winds in northern Sahara lower to 500 mb and the easterlies in the southern Sahara extend to 300 mb.

Mean wind speeds less than 25 knots at all levels indicate the absence of a jet stream for the Sahara. For example, In Salah's wind speeds average less than 25 knots at 300 mb. Figure 4-6 indicates the highest frequencies of winds greater than 40 knots to be at 850 mb.

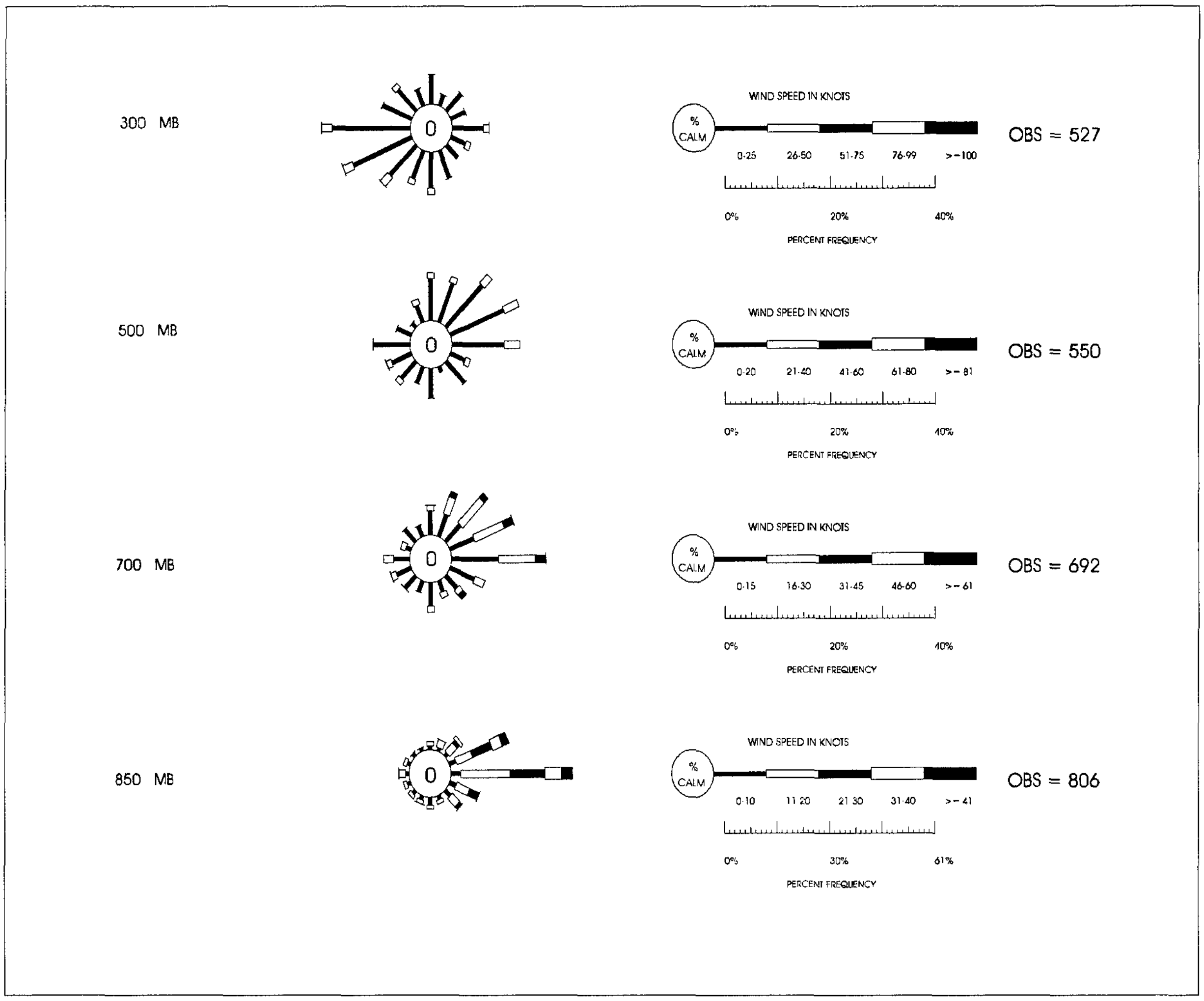


Figure 4-6. July Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at In Salah, Algeria.

Precipitation/Thunderstorms. July through September are typically the wettest months of the year. The greatest amount of precipitation occurs over the southern Sahara due to the influence of the NETWC (Figure 4-7). Figure 4-8 shows the mean number of days with rain and/or thunderstorms for several locations in the Sahara.

The coastal stations of Nouakchott and Villa Cisneros receive most of their precipitation from a combination of the strengthening of the sea breeze and the influence of the NETWC. As seen in Figure 4-7, the southern portion of the Sahara receives 50 to 100 mm of precipitation during the month of August. The northern Sahara receives less than 10 mm. Bechar and Tessalit receive their sparse precipitation from orographic convective activity near the Atlas and Ahaggar Mountains, respectively. At most locations, precipitation is sparse and several months or even years may pass with no rainfall. Precipitation that occurs during a particular day can break a monthly average or even an annual average. Heaviest precipitation occurs along the coast and in the Ahaggar Mountains primarily in the summer when the NETWC is furthest north. Absolute maximum precipitation at the coastal location of Nouakchott was 249 mm in August and Tamanrasset had 48 mm in May and September when the NETWC is migrating to the north and south respectively. Often more moisture evaporates than is gained through precipitation explaining the extreme aridity of the Sahara. Most precipitation is showery except along coastal areas where stratified systems occur. Rain averages approximately 2 rain days a month at most locations (Figure 4-8) with a maximum of 4 rain days occurring at Nouakchott in August and September.

Thunderstorms occur approximately 1 day a month at most locations. Mountainous regions receive somewhat more thunderstorm days. For example, Bechar/Quakda and Tamanrasset receive 2 thunderstorm days a month from orographic affects of the Atlas and Ahaggar Mountains. In August and September, the south coast averages 4 thunderstorm days during the month of August and September. Figure 4-8 indicates Nouakchotts increase from an average of 1 thunderstorm day in June to 4 thunderstorm days in August due to the affects of the NETWC. This is when the NETWC's mean summer time position is north of Nouakchott.

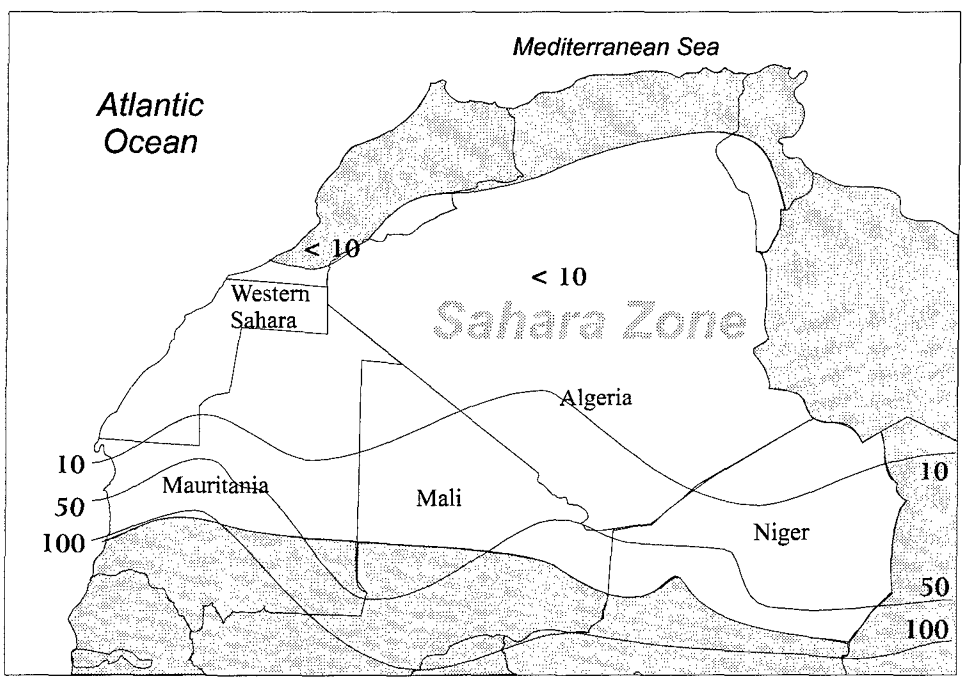


Figure 4-7. August Mean Precipitation (mm). The isopleths show most mean precipitation for August is largely associated with the location of the NETWC.

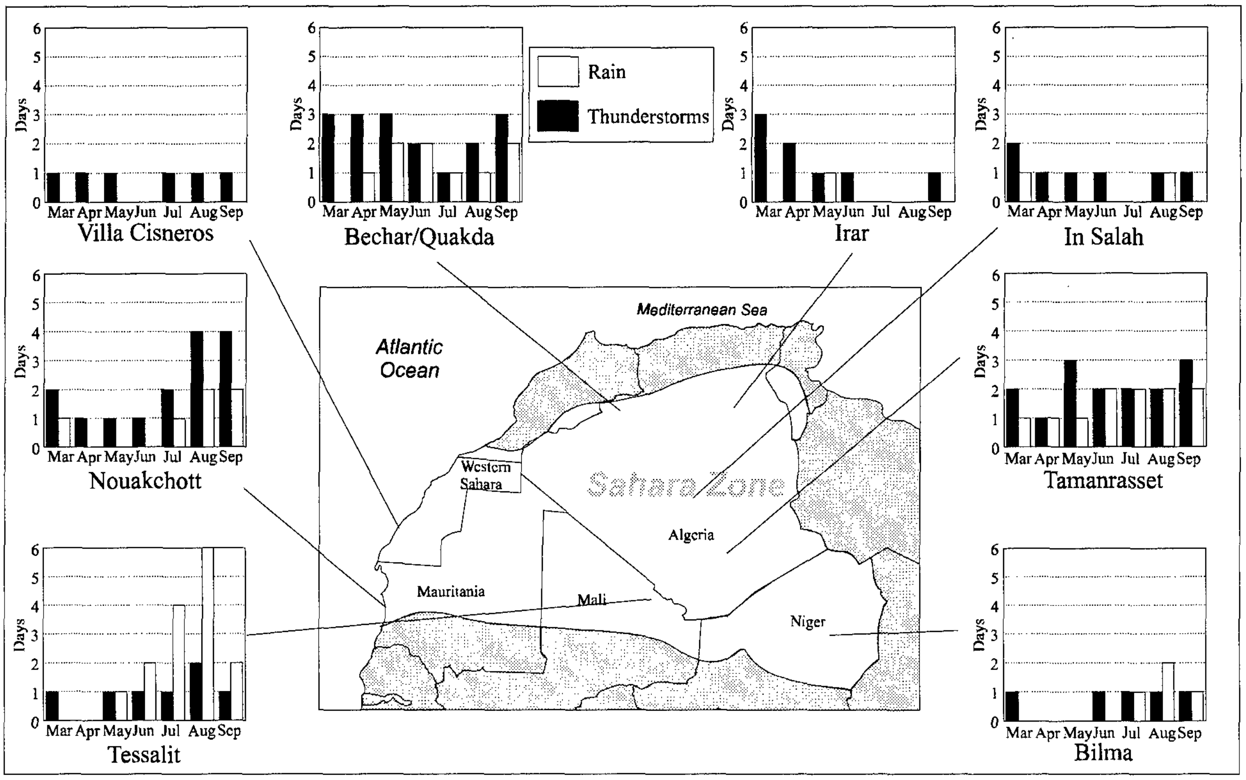


Figure 4-8. Summer Mean Precipitation and Thunderstorm Days. The graphs show the number of days with rain and thunderstorms based on monthly average occurrences at scattered location within the Sahara Zone.

Temperatures. High temperatures in the Sahara are extremely hot. Nearly half the zone has observed extreme maximum temperatures in excess of 50° C. Figure 4-9 shows mean maximum temperatures range from the low 40s in central Algeria to upper 30s elsewhere. Coastal regions have mean maximum temperatures in the mid to upper 20s. The highest temperatures are reached in June and July at most of the northern locations and as early as May and June at southern locations, reflecting the influence of the NETWC on the general weather pattern. Yearly maximum temperatures occur as late as August through October at coastal areas where the maritime influence is so great. The large water mass must become heated before maximum readings are obtained.

Mean minimum temperatures are in the mid to upper 20s in the heart of the Sahara to the lower 20s along coastal regions (Figure 4-10). The average diurnal temperature range for the Sahara is 15° C, but can be as high as 20° C in the northern sections of the Sahara. Along coastal regions and in the Ahaggar Mountains the diurnal temperature range is only 10° C. Radiational cooling can affect the Sahara even during the summer. Extreme minimum temperatures of 0° C have been reported at most locations. The lowest reported absolute minimum temperature was -2° C at Bilma during the month of June.

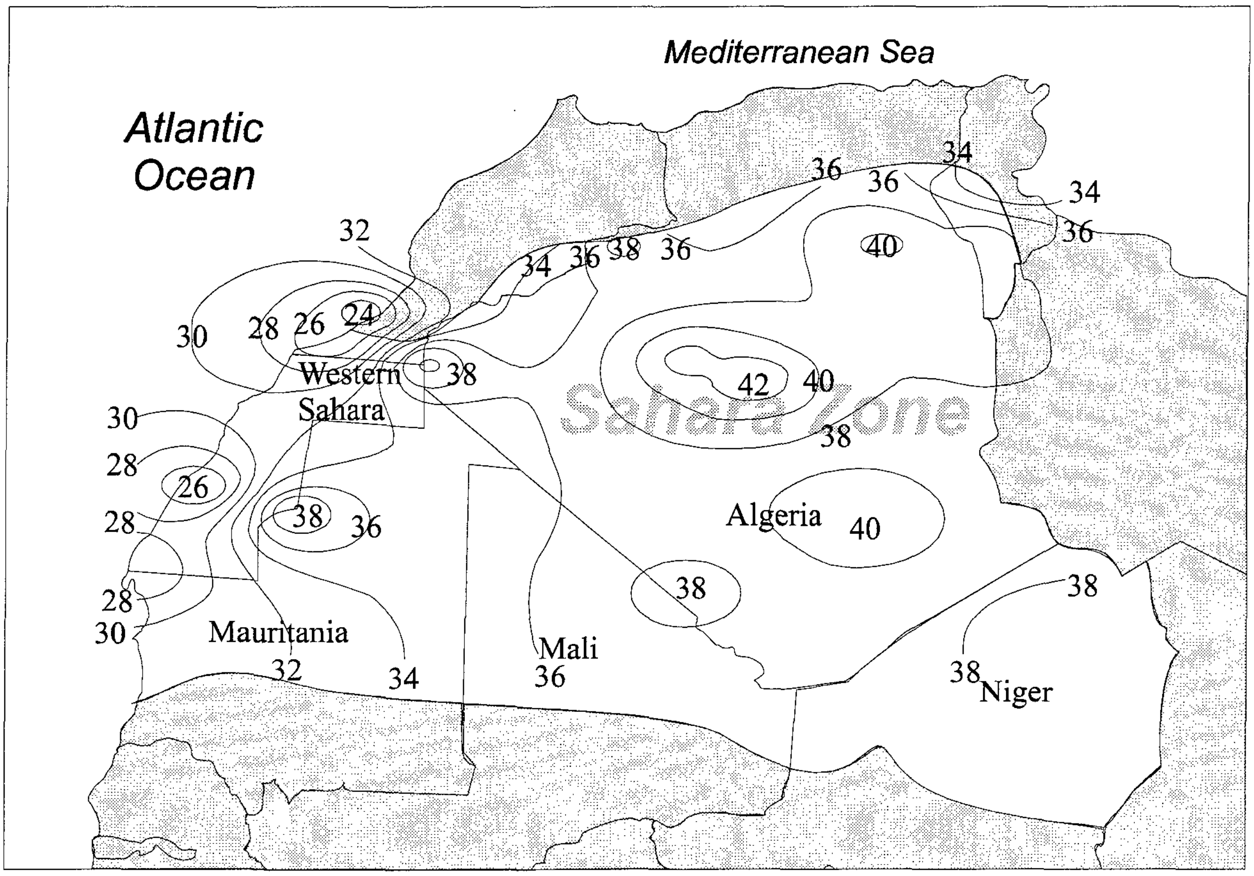


Figure 4-9. August Mean Maximum Temperatures (° C). These temperatures represent the average of all high temperatures for the most representative month of summer. Daily high temperatures are often higher than the mean. Mean maximum temperatures will be lower during early summer.

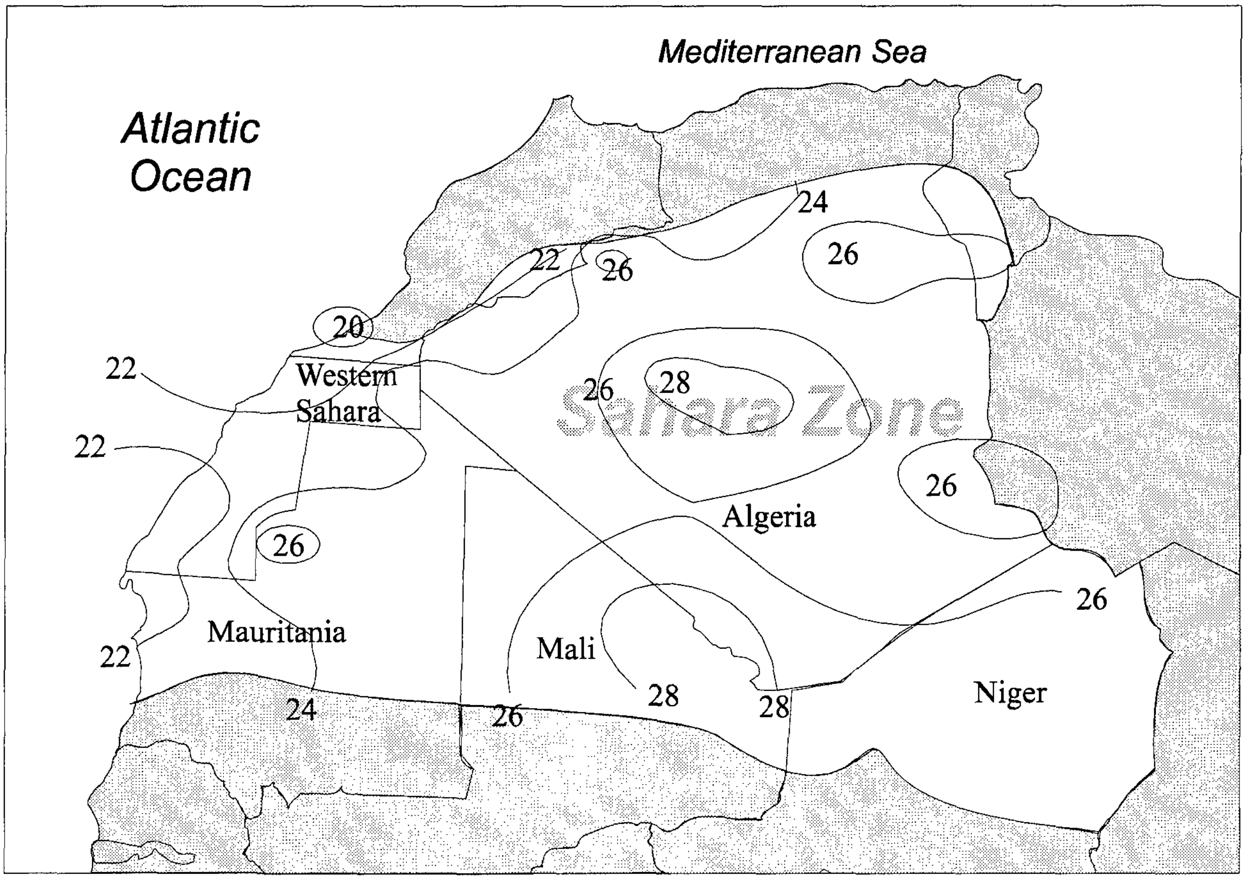


Figure 4-10. August Mean Minimum Temperatures (° C). Mean minimum temperatures represent the average of all low temperatures for August. Daily low temperatures are often lower than the mean. Mean minimum temperatures at the beginning of summer are lower.

Hazards.

Squall Lines. The most significant hazards during the summer season are associated with African squall lines that affect the Sahara south of 20° N. Squall lines typically develop during peak heating periods between 1400 and 1700L. They may last anywhere from 6 hours to 2-3 days and propagate west at 17-45 knots. Significant hazards include gusty surface winds, hail, restricted visibilities in showers, severe turbulence, and icing. Flash floods are always a danger and can destroy sections of roadways and wash out bridges. Thunderstorm tops are normally near 50,000 feet, (15.2 km), but occasionally reach 60,000 feet (18.3 km). Thunderstorms can be even more dangerous when masked by other clouds.

Duststorms/Sandstorms. Duststorms are common when solar heating is strong and mean wind speeds are above 15 knots causing widespread or localized visibility problems. The stronger the winds and the longer the trajectory, the greater the height to which sand and dust are lifted. Duststorms can drop temperatures as much as 15°C and particles can remain suspended for 1-7 hours before settling to the ground. Large temperature contrast during the day between the hot sand surface and cooler air causes extremely unstable conditions that trigger dust devils. Dust devils range in height from 10 to 100 feet (3 to 30 meters) and can raise dust as high as 2,000 feet (600 meters). Duststorms are strongest during the early part of the summer season, when the soil is extremely dry. Strong thunderstorm winds can produce a dry tornado.

Visibilities in duststorms can remain restricted for about 2 hours. Poor visibility may persist for up to 24 hours. Downrush from helicopters and aircraft can raise dust from an undisturbed desert floor. This can lower visibilities around the aircraft, obliterating any visual reference with the ground during takeoffs and landings. The amount of dust raised can be enough to clog filtering equipment, and be ingested into aircraft engines. The ever present dust and low humidity causes dry skin, sore throat, and cracked lips. The dust can also contribute to radio signal degradation. Impact of windblown particles creates the danger of large electrostatic discharges (lightning), putting personnel and equipment at risk.

Soil Temperatures. Intense solar heating causes high ground temperatures. Mid-day soil temperatures greater than 60° C can occur on both sandy and rocky desert surfaces. Mountains in particular, heat up in the hot desert sun. One location on the Asekrem Plateau recorded an extreme maximum soil temperature of 64.3° C at an elevation of 8.950 feet (2,727 meters). The hot soil temperatures of the Sahara lag behind the air temperatures. The hottest soil temperatures occur near midnight. These extremely hot surface temperatures can adversely affect stored supplies, equipment, materials subject to chemical reaction, and personnel.

Density Altitude. The performance of aircraft are related to the density of the air at the time of takeoff. Air density affects lift capacity and how much runway is needed for takeoff. High temperatures, increases in moisture, and low pressure all decrease the density of the air. Thus, aircraft perform better during takeoff on a cool morning rather than a hot afternoon, or at lower elevations rather than higher elevations. Density altitude is a primary concern particularly in the southern Sahara. This is when hot temperatures and increases in moisture content from the migration of the NETWC combine to make density altitude a hazard. Helicopters have their greatest lift and attain highest speeds in air of high density. Thus, pilots of these craft prefer to fly under conditions of low temperature and high pressure, since this is when the air is most dense. Pilots of jet aircraft have a great interest in the density of the air because air density not only affects speed, rate of climb, and fuel consumption, but also plays an important role in determining the length of runway necessary for takeoff.

Turbulence. Heat-induced turbulence over the Sahara is common. Light to moderate conditions, especially during the afternoon hours in the lower 10,000 feet (3 km) of the atmosphere can be expected. Such turbulence can not be considered a serious hazard, though it does create uncomfortable flight conditions for passengers and aircrews. Moderate or greater turbulence can be expected below 10,000 feet (3 km) in and around the Ahaggar and Atlas Mountains with upslope flow and downwind of higher terrain features. Thunderstorms or squall lines are capable of producing severe turbulence.

General Weather. Winter begins in October as the South Atlantic and Azores Highs weaken and migrate back to the south. Polar fronts invade the region with greater frequency and bring sparse precipitation (commonly called Mango rains) to the northern Sahara. These polar invasions can create duststorms and raise a sand wall 2,000 to 3,000 feet (600 to 900 meters) high as winds shift to the northeast behind the front. Visibility can drop to near zero and temperatures can fall as much as 15° C with the dust and cold air behind the cold front. Many of the fronts that cross the Atlas Mountains will only bring scattered clouds and very little precipitation. Precipitation may fall from dense altocumulus or altostratus that occasionally make it across the Atlas Mountains. Much of the precipitation evaporates as it falls through the thick layer of dry air. The southern Sahara receives little rainfall due to the southward retreat of the NETWC.

The Harmattan begins to show its influence in November over the northern Sahara. Dust and sand storms are the major problems that influence the weather. As the Harmattan intensifies throughout the winter, dust and sand storms become more frequent and reach peak frequency in February and March just prior to arrival of the NETWC. Winds greater than 15 knots can drop the visibility to near zero in a matter of minutes, depending on the size, number of particles, wind speed, and terrain. Even in coastal regions, the Harmattan keeps the air dry with little chance for precipitation.

Temperatures steadily decrease between October and January. January is the coldest month at most locations. Due to the extreme dryness of the Saharan air, minimums are much lower than one might expect. Minimum temperatures at inland locations usually drop to approximately 5° C. Some locations experience below freezing temperatures due to strong radiational cooling. Temperatures begin to increase in February as the winter season comes to an end.

Trafficability. Except for the mountainous regions (Atlas and Ahaggar) and the southern Sahara region affected by the NETWC, trafficability changes little from season to season. Trafficability is a measure of the capacity of surface soil to support moving vehicles. The capacity of soil to withstand traffic is a function of soil strength. This in itself depends on the combined effect of grain size and shape, organic matter content, mineral composition, plasticity, density, and moisture content. The Sahara is dominated by coarse-grained soils, large areas of high elongated sand dunes, sand sheets, drifting sand, broad-level sand and gravel plains. Flat-topped and highly dissected plateaus, and many boulder covered areas, including the Ahaggar Mountains also dominate the Sahara.

Winter brings showers to the northern Sahara and along mountains to infrequent squalls along the north coast. Although rainfall is usually meager, occasional violent downpours result in flash floods. The number of dry stream beds (wadis) is tangible evidence of this phenomenon. At times these floods are caused by a heavy rain that is beyond visual range, and the first or perhaps the only indication may be the approach of the rapidly rising water in the stream beds. Strong squalls (strong winds and precipitation) can wash out bridges and roads hindering trafficability in the Ahaggar Mountains and along coastal areas. In winter, flash flooding is most likely in the northern Sahara, and along the northern coast where Atlas Low development creates a higher frequency of heavy squalls. A contributing factor to flooding is the hard or rocky soil that reduces water percolation and also the lack of absorbency of sandy surfaces of the Sahara. Occasional snowfall occurs in northern Algeria and in higher elevations of the Ahaggar Mountains, but is usually melts due to the high diurnal temperature changes and soil temperature. Icy conditions are possible in higher elevations should the air temperature remain below freezing for extended periods of time and the temperature of the road decreases to 0° C. Mount Tahat in the Ahaggar Mountains can become snow capped for a few days during some of the more severe winters, probably as a result of a single snowfall.

Off-road vehicular movement is good to excellent year round on the broad-level sand and gravel plains and flat plateau surfaces. Movement is poor in dune areas, highly dissected areas, and areas of deep and drifting sand. South and east of the Ahaggar Mountains are areas of extensive plateaus. Steep, rugged hills dissect many of these plateaus, causing very slow and winding movement. Mountains, extensive margins of plateaus, and boulder-covered areas restrict movement to existing routes.

Sky Cover. Winter is the driest time of the year for the region and cloud coverage is at a minimum. Except for along coastal regions, the percent frequency of occurrence of any ceiling is less than 30 percent (Figure 4-11). Most of the region observes scattered clouds such as cirrus and occasional middle clouds. The retreat of the NETWC is clearly evident as cloud cover decreases over the southern Sahara compared to that of the summer season (compare Figure 4-11 with Figure 4-2, Page 4-9).

Percent frequency of ceilings less than 3,000 feet (900 meters) is near zero for many inland locations including the Ahaggar Mountains and less than 5 percent for most of the region (see Figure 4-12). Coastal locations also experience a decrease in cloud coverage. They experience ceilings below 3,000 feet (900 meters) only 5-10 percent of the time.

Nearly all locations receive ceilings below 1,000 and 500 feet (300 and 150 meters) less than 5 percent of the time. However, Villa Cisneros receives ceilings below 1,000 and 500 feet (300 and 150 meters) 13 and 6 percent of the time, respectively. The north coast receives a stronger oceanic influence and it is not affected by the Harmattan as much as the southern coastal region. The retreat of the NETWC, the weakening of the sea breeze, and the predominant offshore winds all contribute to the decrease in cloud coverage along the coast. The Ahaggar Mountains experience fewer low ceilings in winter than during summer. For example, Tamanrasset receives ceilings below 500 feet (150 meters) less than 2 percent of the time. This accounts for nearly all their observed ceilings less than 3,000 feet (900 meters) (see Figure 4-12).

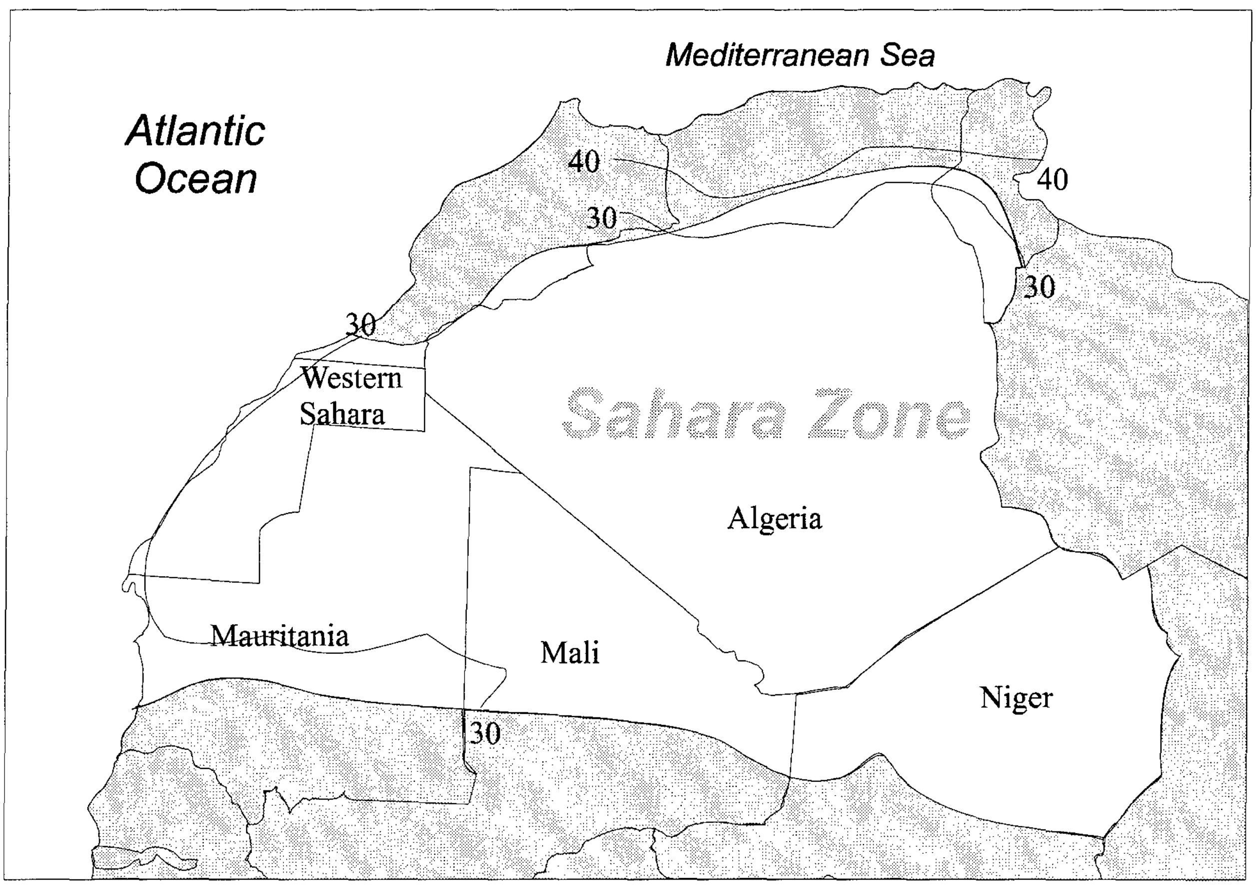


Figure 4-11. January Percent Frequencies of Ceilings. The isopleths represent the frequency of cloud ceilings at all altitudes for local noon.

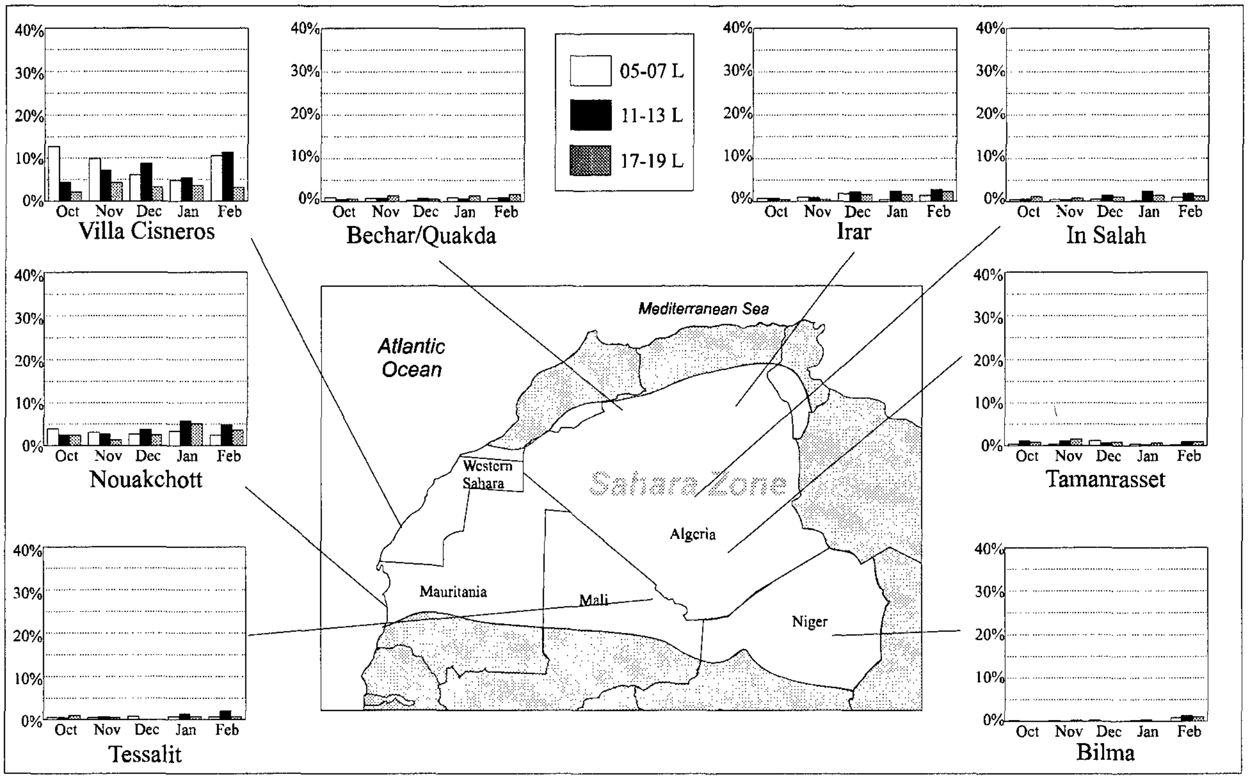


Figure 4-12. Winter Percent Frequencies of Ceilings Below 3,000 Feet (900 Meters). The graphs show a monthly breakdown on the percentage of ceilings below 3,000 feet (900 meters) based on location and diurnal influences.

Visibility. The majority of visibility problems are the result of sand and dust raised by the Harmattan. Atlas Lows with their associated cold fronts occasionally invade northern sections of Algeria (south of Atlas Mountains), bringing with them a wall of dust that can lower the visibility to near zero in a matter of minutes.

Visibility less than 4,800 meters occurs 5-10 percent of the time over the northern and central Sahara where the Harmattan is not as prominent. However, over the southern and western Sahara, visibilities less than 4,800 meters occur anywhere from 10-45 percent of the time (see Figure 4-13). Southern coastal locations like Nouakchott experience a significantly higher percent frequency of visibility less than 4,800 meters due to dust and sand raised by the Harmattan on its long trajectory across the desert. Lack of precipitation and the strengthening of the Harmattan combine to create the higher frequencies of low visibilities seen in Figure 4-13 from December through February. With the NETWC positioned well to the south of the Sahara, Harmattan haze becomes more of a surface based phenomena.

Most locations observe visibilities of 1,600 and 800 meters only 5 percent of the time. The southwestern sections of the Sahara receive a strong continental influence; therefore, significantly higher frequencies of low visibilities occur there compared to the rest of the Sahara. For example, Nouakchott had visibilities below 1,600 and 800 meters 26 and 13 percent of the time, respectively; Villa Cisneros had visibilities in those categories only 5 percent of the time. Most visibility restrictions are due to blowing dust and sand along the south coast; however, along the north coast, fog occurs almost as frequently as blowing dust. In January, Nouakchott had 17 blowing sand days and 3 fog days; on the other hand, Villa Cisneros received 4 blowing sand days and 3 fog days.

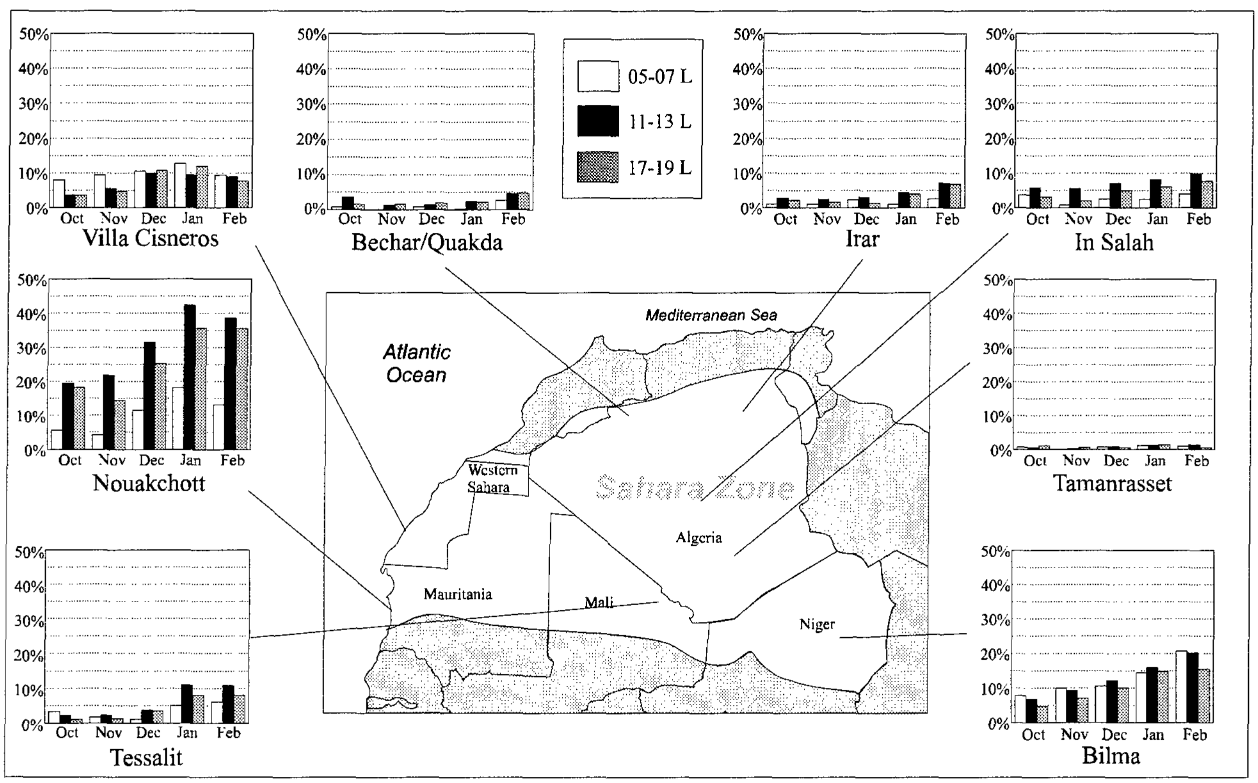


Figure 4-13. Winter Percent Frequencies of Visibilities Below 4,800 Meters. The graphs show a monthly breakdown on the percentage of visibilities below 4,800 meters based on location and diurnal influences.

Winds. During winter, the Saharan High dominates the surface pressure pattern thereby affecting the wind pattern. Predominate winds are east to northeast (Harmattan) at nearly all locations (see Figure 4-14). With the retreat of the NETWC and strengthening of the Saharan High, northeasterly flow replaces the predominant southwest flow that affected the southern Sahara during summer. As shown in Figure 4-14, the northern Sahara (Bechar/Quakda and Irar) receive a high frequency of south through southwest winds ahead of Atlas Lows as they move eastward.

Wind speeds are generally between 6-15 knots, much like the summer season. Bilma has the highest reported mean wind speeds in excess of 35 knots because of the funneling effect of the Grand Erg de Bilma. Maximum wind speeds near 65 knots have been reported at Bilma from November-January.

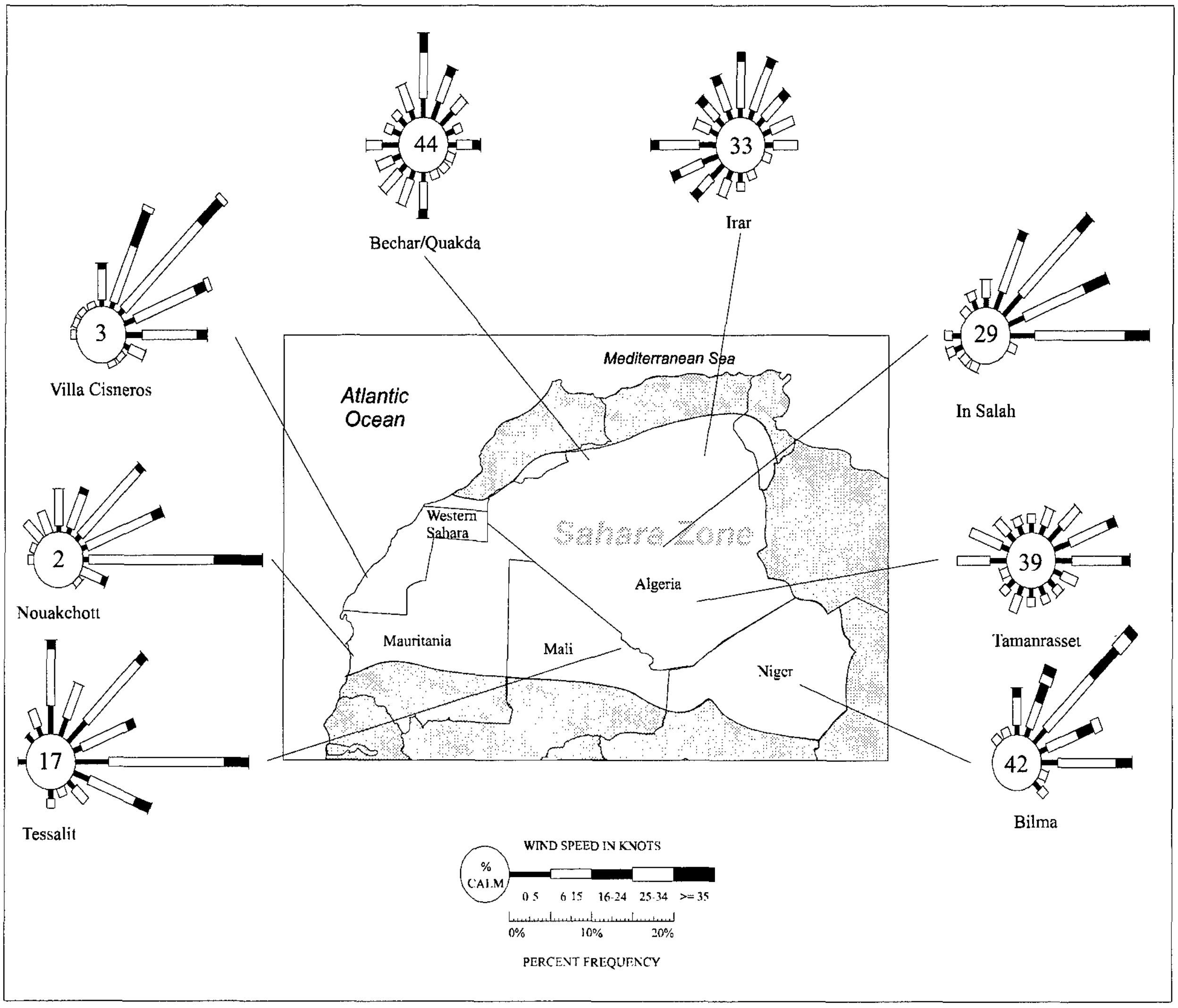


Figure 4-14. January Surface Wind Roses. The figure shows prevailing wind direction and range of speeds based on percent of frequency and location.

Winds Aloft. The Mean PFJ is located in Europe, but on rare occasions can dip into the northern Sahara at a mean height of 300 mb. The mean STJ (see Figure 2-7) is located from Mauritania through southern Algeria at a mean height of 200 mb. The east through northeast flow at 850-500 mb over In Salah in summer (Figure 4-6) becomes much shallower (Figure 4-15). As the mean position of the STJ moves southward (Figure 2-7), the predominant easterly winds of summer are replaced by westerlies above 700 mb, (see Figure 4-15 and Figures 2-11 to 2-14). At 850 mb, winds remain northeasterly, reflecting the vertical extent of the Saharan High. Wind directions vary between northerly and westerly at 700 mb.

Wind speeds show a dramatic increase in winter. At 300 mb, typical wind speeds are between 51-75 knots as opposed to the 26-50 knots reported in summer. Maximum wind speeds within the PFJ are normally 60-100 knots at 300 mb. Within the STJ, winds normally reach 80-90 knots, but may exceed 100 knots at 200 mb. Mean wind speeds may exceed 80 knots at 500 mb.

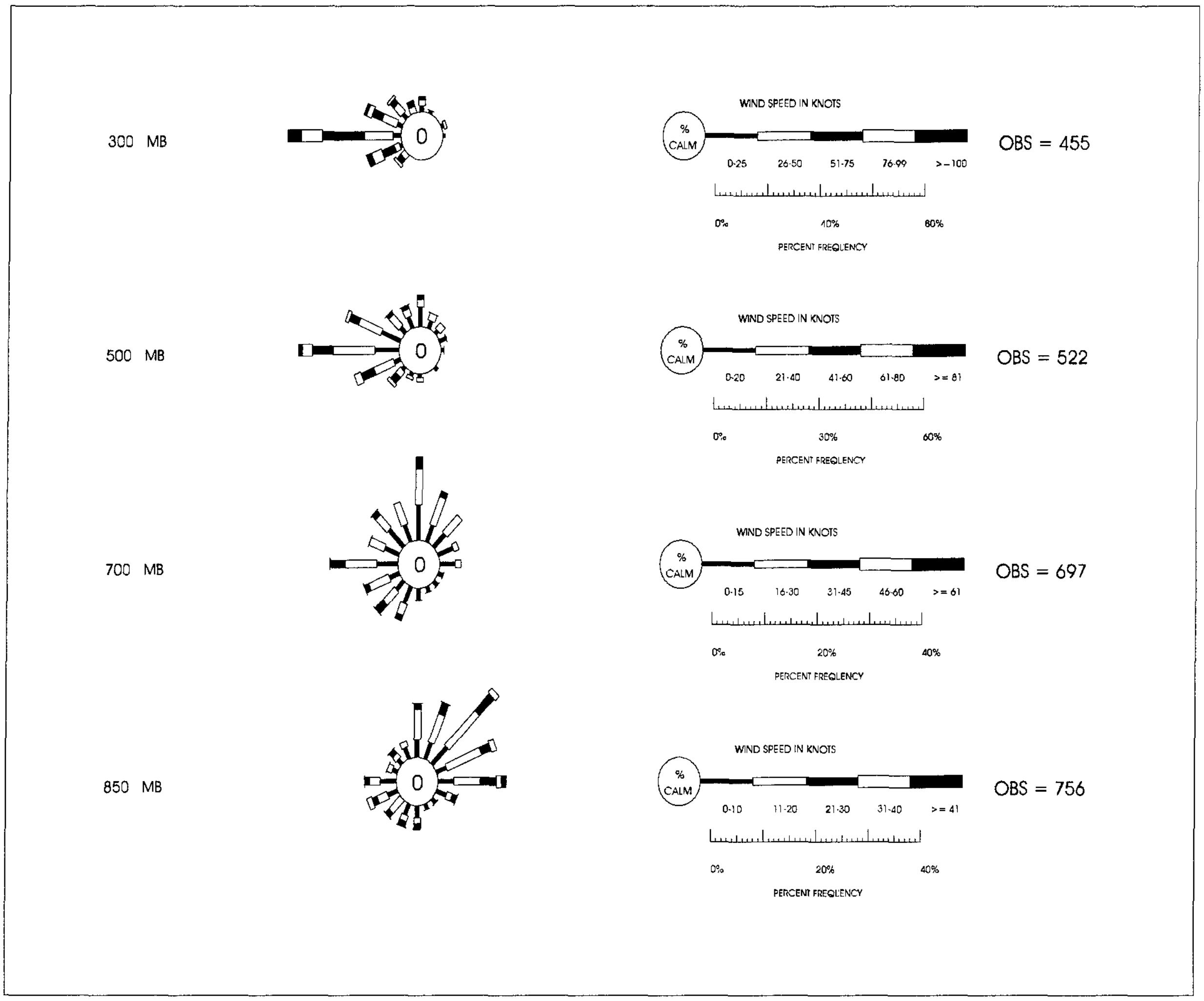


Figure 4-15. January Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at In Salah, Algeria.

Precipitation/Thunderstorms. Very little precipitation occurs over the Sahara in winter. Precipitation amounts for each of the winter months are less than 10 mm over most of the region (see Figure 4-16). Absolute maximum precipitation for winter occurs at Bilma with 49 mm of precipitation in October. The most noticeable change from summer is over the southern Sahara where the NETWC is replaced by the dry Harmattan winds. Both Tessalit and Bilma see a dramatic decrease in thunderstorm and rain days. Rain days at Tessalit drop from 15 in summer to 1 day in winter (Figure 4-17). The majority of the thunderstorms have no precipitation associated with them. In the northern Sahara there is little change in the number of rain and thunderstorm days from summer to winter. Most of the precipitation is associated with frontal systems trailing from Atlas Lows. Most precipitation received is liquid, but snow is possible in northern Algeria and in the highest areas of the Ahaggar Mountains. However, the snow melts quickly and usually doesn't accumulate.

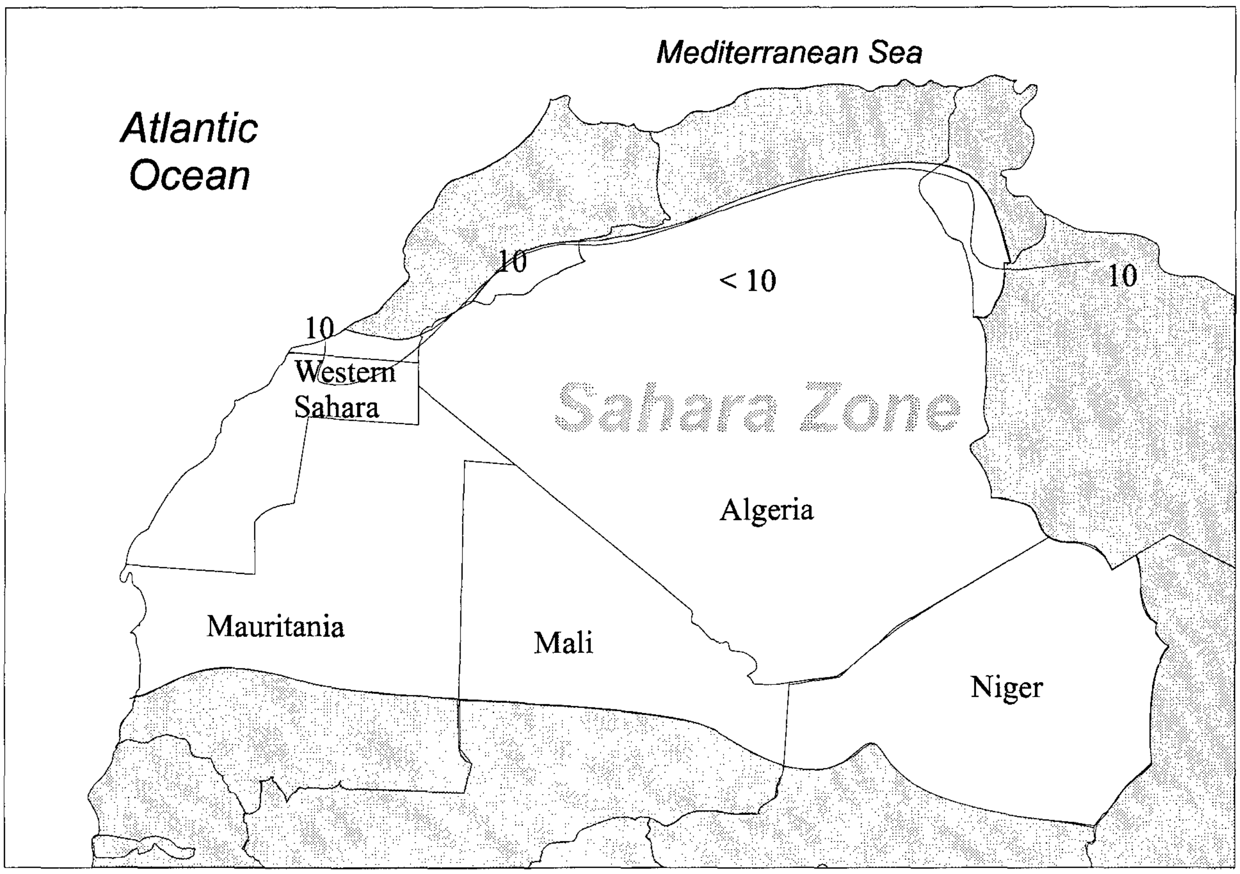


Figure 4-16. January Mean Precipitation (mm). The limited isopleths depict the small amount of precipitation that occurs over the Sahara Zone in winter.

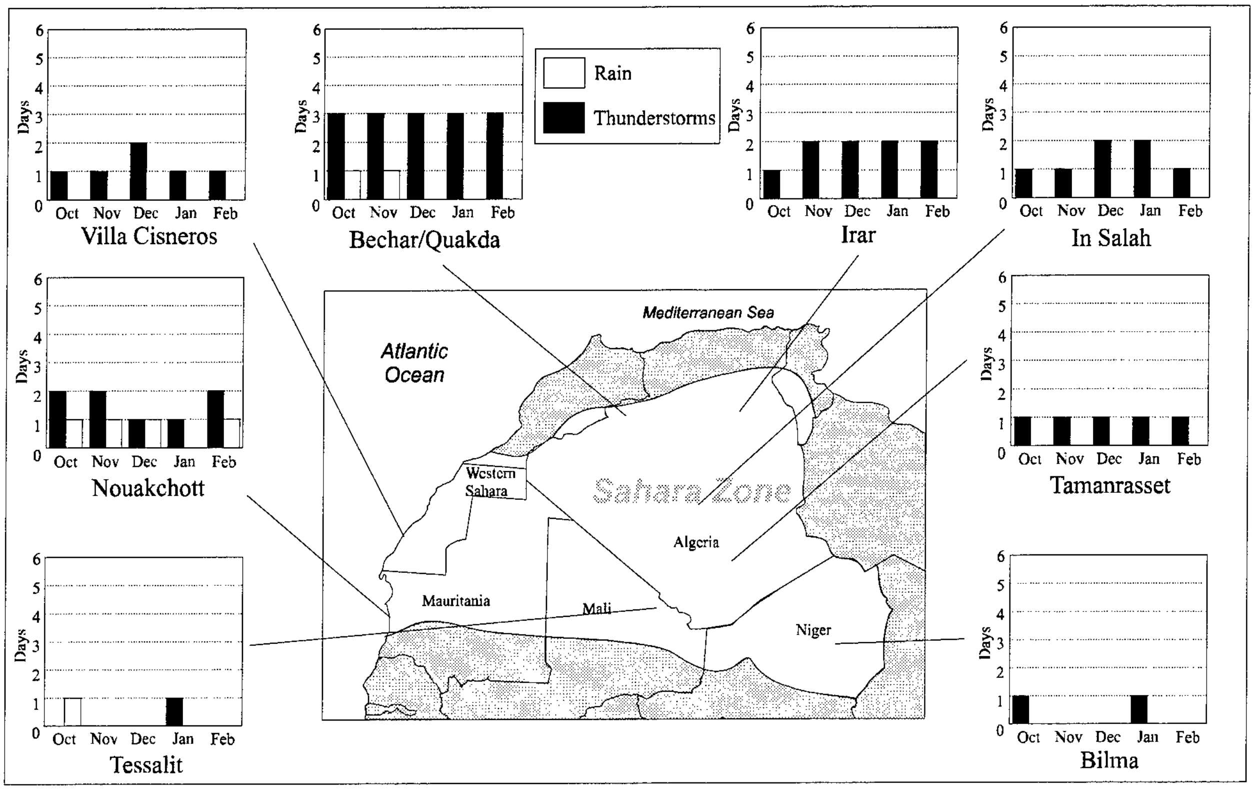


Figure 4-17. Winter Mean Precipitation and Thunderstorm Days. The graphs show the average wintertime occurrence of rain and thunderstorm days for selected cities in the Sahara Zone.

Temperatures. The lowest temperatures of the year are recorded in winter, primarily due to the low humidities and strong radiational cooling. January is the coldest month with average highs ranging from less than 16° C in the north to 26° C in the south (Figure 4-18). Absolute maximum temperatures range in the middle 30s in the southern Sahara to the mid-20s in northern Sahara. Villa Cisneros recorded an extreme maximum temperature for January of 41° C.

Average lows range from less than 5° C in the north to more than 15° C in the south (Figure 4-19). Temperatures can reach 0° C in the extreme northern Sahara and in higher elevations such as the Ahaggar Mountains. Tamanrasset recorded an absolute minimum temperature of -6° C.

Temperatures at coastal stations are modified by the Atlantic Ocean. Coastal areas experience a smaller diurnal temperature range than do inland stations. For example, the diurnal temperature range at Villa Cisneros is only 6° C whereas at Bilma there is a 14° C difference between the mean daily maximum and minimum temperature. Diurnal variations as much as 30° C can occur at some desert locations.

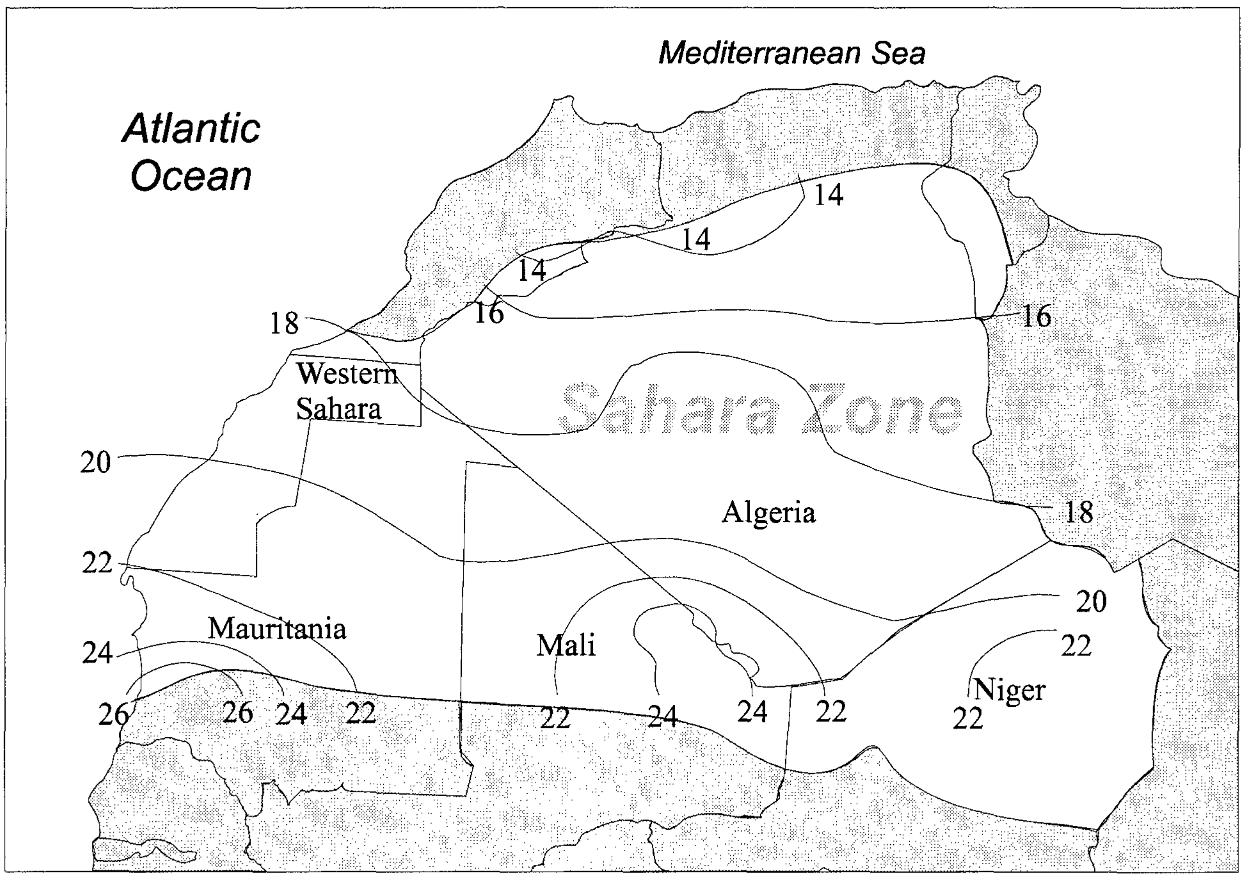


Figure 4-18. January Mean Maximum Temperatures (° C). The isopleths represent the average of all high temperatures for the most representative month of winter. Daily high temperatures often will be higher than the mean. Mean maximum temperatures during early winter will be higher.

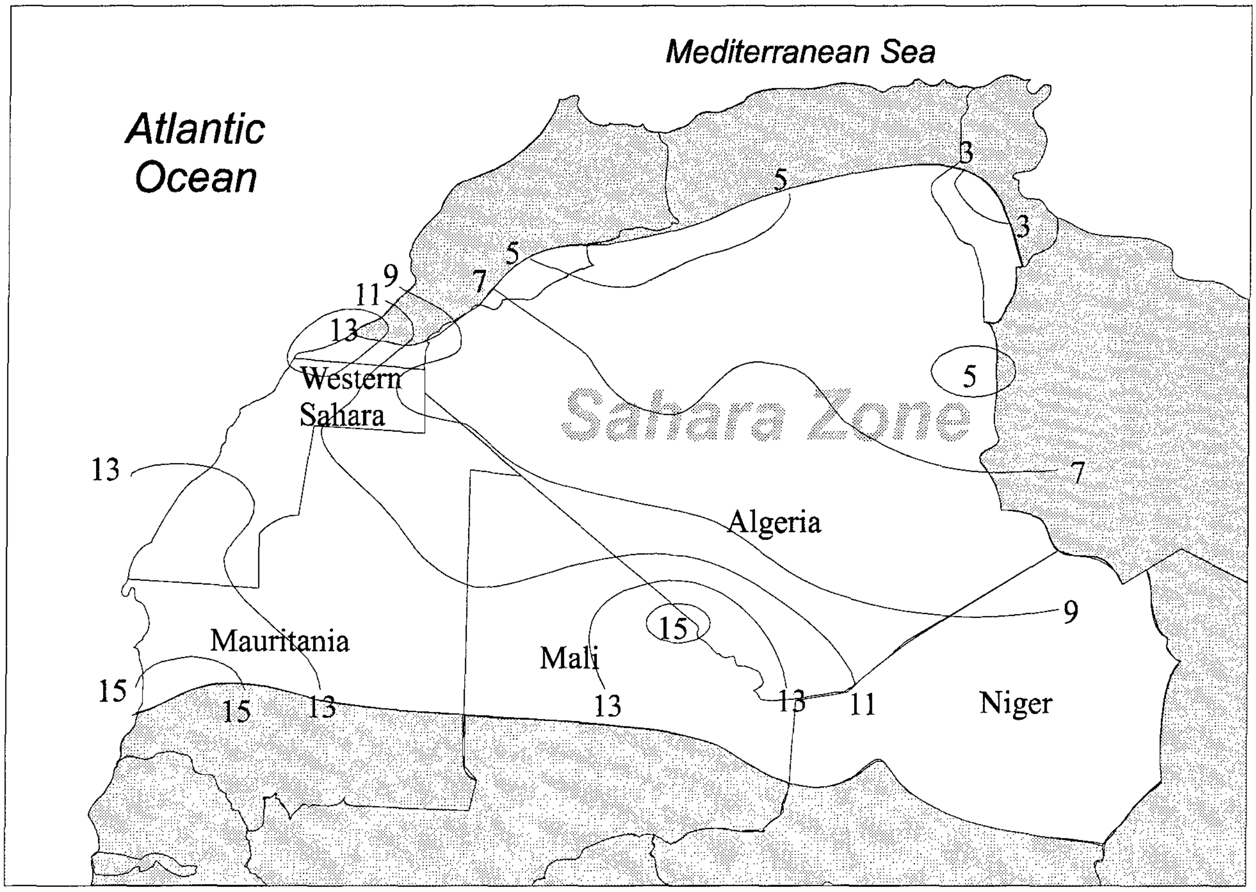


Figure 4-19. January Mean Minimum Temperatures (° C). Mean minimum temperatures represent the average of all low temperatures for the most representative month of winter. Daily low temperatures are often lower than the mean. Mean minimum temperatures at the beginning of winter are warmer.

Hazards.

Duststorms/Sandstorms. Duststorms, the most common hazard of the winter season, can cause widespread or localized visibility problems. They occur when solar heating is strong and mean wind speeds are above 15 knots. Duststorms become more common and more severe toward the end of the winter season when the Harmattan is at its strongest and the soil is the driest. Although duststorms are the most common hazard; they do not occur as frequently as summer. Duststorms occur approximately 5 days per month at most locations. The stronger the winds and the longer the trajectory, the greater the height to which sand and dust are lifted. Large temperature contrasts during the day between the hot sand surface and cooler air causes extremely unstable conditions that trigger dust devils 10 to 100 feet (3 to 30 meters) in height and can raise dust as high as 2,000 feet (600 meters). Visibilities in duststorms can approach zero and usually last for about 2 hours, but can persist for up to 24 hours. Sandstorms are composed of heavier particles that remain suspended below 6 feet (1.8 meters) and settle quickly. Downrush from helicopters and aircraft can raise dust from an undisturbed desert floor. This can lower visibilities around the aircraft, obliterating any visual reference with the ground during takeoffs and landings. The amount of dust raised can be enough to clog filtering equipment, and be ingested into aircraft engines. The ever present dust and low humidity causes dry skin, sore throat, and cracked lips. The dust can also contribute to radio signal degradation. Impact of windblown particles creates the danger of large electrostatic discharges (lightning) putting personnel and equipment at risk.

Turbulence. Even though winter is the coldest season, heat-induced turbulence affects the Sahara during the afternoon hours. Light to moderate turbulence can be expected below 10,000 feet. Such turbulence can not be considered a serious hazard, though it does create uncomfortable flight conditions for passengers and aircrews. Moderate or greater turbulence can be expected below 10,000 feet (3 km) in and around the Ahaggar and Atlas Mountains, with upslope flow and downwind of higher terrain features. Thunderstorms or squall lines are capable of producing severe turbulence. Turbulence above 10,000 feet (3 km) is rare, but occasional light to moderate indensities can be expected below the tropopause when the jet stream is present. The average January tropopause height is normally 11 km.

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